Defence Research and **Recherche et développement**
Development Canada **pour la défense Canada**

DEFENCE **R&D** DÉFENSE

Single High Fidelity Geometric Data Sets for LCM – Model Requirements

D. Brennan
T. Koko
K. Mackay
M. Norwood
S. Tobin
E. Teng
J. Wallace
Martec Limited

Martec Limited
Suite 400, 1888 Brunswick St.
Halifax, Nova Scotia B3J 3J8

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2006-134
November 2006

Canada

This page intentionally left blank.

Single High Fidelity Geometric Data Sets for LCM – Model Requirements

D. Brennan
T. Koko
K. Mackay
M. Norwood
S. Tobin
E. Teng
J. Wallace
Martec Limited

Martec Limited
1888 Brunswick Street, Suite 400
Halifax, Nova Scotia
B3J 3J8

Defence R&D Canada – Atlantic

Contract Report

Author

D. Brennan

Approved by

D.C. Stredulinsky

Contract Scientific Authority

Approved for release by
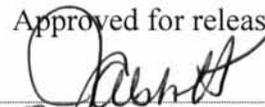
Kirk Foster

A/DRP Chair

The scientific or technical validity of this Contract Report is entirely the responsibility of the contractor and the contents do not necessarily have the approval or endorsement of Defence R&D Canada.

Abstract

Over the past decade, the ship building industry has begun to develop and use Single Product Models (SPMs) for improving the management and efficiency of design, analysis and construction of commercial and naval vessels. SPMs are extensive single 3D CAD data models incorporating hull structure, propulsion, steering, piping, electrical, HVAC and other systems, which make up a complete ship. Ship classification societies and navies (most notably the USN in their DDX project) have ongoing R&D efforts to bring this technology to its full potential. This work involves leading software providers, including Tribon, Catia and ShipConstructor who are developing products, training and documentation to facilitate the use of SPMs by ship builders and design authorities. It is reasonable to expect that future DND vessels will be designed and built using SPMs.

During this same period of time, DND has had an ongoing R&D effort in developing computer-aided ship data and analysis programs to improve the efficiency of Life Cycle Management (LCM - maintenance) of its fleet. Martec Ltd has been extensively involved in this work, most notably through the DRDC ISSMM (Improved Ship Structures Maintenance Management) Technology Demonstration Program which successfully demonstrated the concept of using a CAD-like database of the HALIFAX class along with advanced sea load and structural analysis methods to determine the effects of structural damage on a vessel's ability to undertake intended operations. The ISSMM project, as well as other DND programs such as the Structural Inspection Database (SID) and the TRIDENT program, which is a general purpose ship structural analysis tool recently developed further by Martec to address FELEX issues, provide an extensive set of software tools to address structural LCM issues.

There is strong interest by ship owners and agencies (including DND and ship Classification societies) and the SPM software producers to extend the SPM applications beyond design and construction to the LCM of ships. Doing so would eliminate the time consuming and costly production of separate analysis models required as input to a number of DND's suite of lifecycle maintenance analysis tools. This offers significant potential savings in operation and maintenance costs as well as improved understanding and confidence in vessel safety. The work proposed under this contract will provide the first steps towards developing a link that can bridge the gap between these LCM analysis tools and data stored in a SPM database. For its part, Martec Limited has worked extensively with DRDC Atlantic in both the development and application of many of these LCM analysis tools, and has recently initiated an in-house R&D program focused on developing SPM/LCM data exchange links. This corporate experience has enabled Martec to offer a uniquely qualified and strong team that can meet the requirements of the proposed R&D effort.

Résumé

Au cours de la dernière décennie, l'industrie de la construction des navires a commencé à développer et à utiliser des modèles de produit uniques (MPU) pour améliorer la gestion et l'efficacité de la conception, de l'analyse et de la construction de navires de guerre et de navires commerciaux. Les MPU sont des modèles de données CAD 3D uniques et complets, incluant la structure de la coque, la propulsion, l'appareil à gouverner, les canalisations, le matériel électrique, le CVC et d'autres systèmes, qui composent la totalité d'un navire. Les sociétés de classification de navires et les forces navales (tout particulièrement l'USN et son projet DDX) ont entrepris des travaux de R & D pour réaliser le plein potentiel de ces technologies. Ces travaux impliquent des fournisseurs de logiciel majeurs, notamment Tribon, Catia et ShipConstructor, qui élaborent des produits, de la formation et de la documentation pour faciliter l'utilisation des MPU par les constructeurs de navires et les responsables de la conception. Il est raisonnable de s'attendre à ce que les nouveaux navires du MDN soient conçus et construits en fonction des MPU.

Parallèlement, le MDN a aussi entrepris des travaux de R & D pour développer des programmes informatiques de collecte et d'analyse des données sur les navires afin d'améliorer l'efficacité de la gestion du cycle de vie du matériel (GCVM – maintenance) de sa flotte. Martec Ltd a grandement participé à ces travaux, tout particulièrement dans le cadre du programme de démonstration technologique GAMSN (Gestion améliorée de la maintenance de la structure des navires) de RDDC, qui a démontré avec succès le concept d'utilisation d'une base de données de type CAD de la classe HALIFAX conjointement avec des méthodes évoluées d'analyse structurale et d'analyse des charges en mer pour déterminer les effets des dommages structuraux sur la capacité d'un navire à mener à bien les opérations auxquelles il est destiné. Le projet de GAMSN et d'autres programmes du MDN, tels que la base de données des inspections structurales (BDIS) et le programme TRIDENT, qui est un outil polyvalent d'analyse structurale générale des navires, dont Martec a récemment poursuivi le développement pour les besoins du FELEX, fournissent un ensemble complet d'outils logiciels s'appliquant aux aspects structuraux de la GCVM.

Les propriétaires de navires, les organismes (y compris le MDN et les sociétés de classification de navires) et les producteurs de logiciels de MPU sont fortement intéressés à étendre les applications de MPU au-delà de la conception et de la construction, soit à la GCVM des navires. Il serait ainsi possible d'éliminer la production coûteuse en termes d'argent et de temps de modèles d'analyse distincts requis comme entrée pour divers ensembles d'outils d'analyse de maintenance du cycle de vie du matériel du MDN. Il pourrait en résulter des économies importantes sur les coûts de maintenance et d'opération, ainsi qu'une meilleure compréhension de la sécurité des navires et plus de certitude dans ce domaine. Les travaux proposés en vertu de ce contrat constitueront les premières étapes vers le développement d'une passerelle entre les outils d'analyse de GCVM et les données stockées dans une base de données de MPU. Martec Limited a beaucoup travaillé avec RDDC Atlantique dans le développement et l'application d'un grand nombre de ces outils d'analyse de GCVM, et a récemment lancé un programme interne de R & D portant essentiellement sur le développement de liens d'échange de données MPU/GCVM. Cette expérience a permis à Martec de mettre sur pied une équipe solide et particulièrement qualifiée, capable de répondre aux exigences des travaux de R & D proposés.

Executive summary

Introduction: Over the past decade, the ship building industry has begun to develop and use Single Product Models (SPMs) for improving the management and efficiency of design, analysis and construction of commercial and naval vessels. SPMs are extensive single 3D CAD data models incorporating hull structure, propulsion, steering, piping, electrical, HVAC and other systems. During this same period of time, DND has had an ongoing R&D effort in developing computer-aided ship data and analysis programs to improve the efficiency of Life Cycle Management (LCM - maintenance) of its fleet. The DRDC ISSMM (Improved Ship Structures Maintenance Management) Technology Demonstration Program successfully demonstrated the concept of using a CAD-like database of the HALIFAX class along with advanced sea load and structural analysis methods to determine the effects of structural damage on a vessel's ability to undertake intended operations. There is strong interest by ship owners and agencies (including DND and ship Classification societies) and the SPM software producers to extend the SPM applications beyond design and construction to the LCM of ships.

Principal Results: Data requirements were reviewed for global structural finite element analysis (FEA), detailed structural FEA, ship hydrodynamics, and the analysis of radar signature, infrared signature, electric potential signature and cathodic protections, magnetic signature, acoustic signature and flow noise. A number of CAD/CAM tools including CADDS5, Tribon, Foran, CATIA, Intergraph and ShipConstructor were reviewed.

Significance of Results: The work conducted under this contract provides the first steps towards developing a link that can bridge the gap between LCM analysis tools and data stored in a SPM database. Doing so would eliminate the time consuming and costly production of separate analysis models required as input to a number of DND's suite of lifecycle maintenance analysis tools. This offers significant potential savings in operation and maintenance costs as well as improved understanding and confidence in vessel safety.

Future Plans: A DRDC Defence Industrial Research project has recently been awarded to Martec Limited with the goal of developing a bridge between SPMs and finite element based structural analysis tools for LCM. A DRDC Atlantic Applied Research Program (ARP) project "Investigation of LCM through Single Product Models" has also recently started with the objective of developing a SPM framework facilitating analysis for LCM in the various technical disciplines of structures, hydrodynamics, signatures, cathodic protection and material and degradation management. This report will form that starting point of this work which is anticipated to result in SPMs for use in LCM analysis of existing and future classes of Canadian naval vessels.

Sommaire

Introduction: Au cours de la dernière décennie, l'industrie de la construction des navires a commencé à développer et à utiliser des modèles de produit uniques (MPU) pour améliorer la gestion et l'efficacité de la conception, de l'analyse et de la construction de navires de guerre et de navires commerciaux. Les MPU sont des modèles de données CAD 3D uniques et complets, incluant la structure de la coque, la propulsion, l'appareil à gouverner, les canalisations, le matériel électrique, le CVC et d'autres systèmes. Parallèlement, le MDN a aussi entrepris des travaux de R & D pour développer des programmes informatiques de collecte et d'analyse des données sur les navires afin d'améliorer l'efficacité de la gestion du cycle de vie du matériel (GCVM – maintenance) de sa flotte. Le programme de démonstration technologique GAMSN (Gestion améliorée de la maintenance de la structure des navires) de RDDC a démontré avec succès le concept d'utilisation d'une base de données de type CAD de la classe HALIFAX conjointement avec des méthodes évoluées d'analyse structurale et d'analyse des charges en mer pour déterminer les effets des dommages structuraux sur la capacité d'un navire à mener à bien les opérations auxquelles il est destiné. Les propriétaires de navires, les organismes (y compris le MDN et les sociétés de classification de navires), et les producteurs de logiciels de MPU sont fortement intéressés à étendre les applications de MPU au-delà de la conception et de la construction, soit à la GCVM des navires.

Résultats principaux: Les exigences relatives aux données ont été examinées pour les besoins de l'analyse structurale générale par éléments finis, de l'analyse structurale détaillée par éléments finis, de l'hydrodynamique des navires et de l'analyse de la signature radar, de la signature infrarouge, de la signature de potentiel électrique et des protections cathodiques, de la signature magnétique, de la signature acoustique et du bruit d'écoulement. Divers outils de CAO/FAO, notamment CADDS5, Tribon, Foan, CATIA, Intergraph et ShipConstructor, ont été examinés.

Importance des résultats: Les travaux exécutés en vertu de ce contrat constituent les premières étapes vers le développement d'une passerelle entre les outils d'analyse de GCVM et les données stockées dans une base de données de MPU. Il serait ainsi possible d'éliminer la production coûteuse en termes d'argent et de temps de modèles d'analyse distincts requis comme entrée pour divers ensembles d'outils d'analyse de maintenance du cycle de vie du matériel du MDN. Il pourrait en résulter des économies importantes sur les coûts de maintenance et d'opération, ainsi qu'une meilleure compréhension de la sécurité des navires et plus de certitude dans ce domaine.

Travaux futurs: Un projet de recherche industrielle de défense de RDDC a récemment été attribué à Martec Limited dans le but d'élaborer une passerelle entre les MPU et des outils d'analyse structurale fondés sur les éléments finis pour les besoins de la GCVM. De plus, un projet du Programme de recherches appliquées (PRA) de RDDC Atlantique intitulé « étude de la GCVM à l'aide de modèles de produit uniques », a récemment été lancé dans le but de créer un cadre de MPU facilitant l'analyse de la GCVM dans les disciplines techniques des structures, de l'hydrodynamique, des signatures, de la protection cathodique et de la gestion du matériel et de la dégradation. Le rapport qui en résultera formera le point de départ de ces travaux, qui devraient permettre d'utiliser les MPU dans l'analyse de la GCVM des classes actuelles et futures de vaisseaux de guerre canadiens.

D. Brennan, T. Koko, K. Mackay, M. Norwood, S. Tobin, E. Teng, J. Wallace. 2006. *Ensemble de données géométriques haute fidélité uniques pour la GCVM – Exigences du modèle*. RDDC Atlantique CR 2006-134. R et D pour la défense Canada - Atlantique.

Table of contents

List of figures

List of tables

This page intentionally left blank.

1.   Introduction

A Canadian naval ship must function dependably and with stealth in a wide variety of operating conditions and over the lifetime of the ship. To do so a number of structural integrity and operational parameters must be met. In order to ensure that its ships are operating within acceptable parameters, DND utilizes a number of structural lifecycle management (LCM) analysis tools. Some of these tools are used to assess the structural integrity of the ship, while others are used to evaluate the ability of the ship to operate with stealth. Each tool has its own input data requirements. Assessing fatigue crack initiation and growth requires extremely fine descriptions of the crack sites that may require description of connection details, including weld profiles. On the other hand, most signature prediction and management tools do not require the same level of detail. For example, the acoustic electric field signature tools employed by DND require only a coarse description of the wetted portion of a ship hull and some pertinent underwater appendages.

Due to the different modelling requirements of the various LCM tools, a great deal of effort and expense can be incurred in developing suitable models for each tool, even though the same ship is being described for each type of analysis.

While data requirements between the various analytical tools vary, all LCM analysis tools depend on a similar geometric description of the ship. In all cases the basic ship geometry is the same. The differences are only in the level of detail, the portion of the ship to be modelled and the data format. A typical Single Product Model (SPM) database should contain most, if not all, of the geometric data required by DND's LCM analytical tools.

In order to address the high cost of developing the ship model data required by each of DND's current suite of ship structural lifecycle management analysis tools, Martec is proposing to investigate the feasibility of using a single high-fidelity geometric ship model, such as the Single Product Model, for some or all DND LCM data requirements. The ultimate goal of this effort is to develop a link that can bridge the gap between these analysis tools and the data stored in a SPM database (see Figure 1.1).

The main advantage of such a system is that the SPMs that are delivered as part of new builds, or developed for existing naval vessels, can be readily incorporated into an improved and more efficient LCM program that takes advantage of recent DRDC technology advances. This should significantly reduce the time and cost of using DND's LCM analytical tools.

A linked system, as shown in Figure 1.1, is practical because the input to DND's LCM tools is, for the most part, based on the same overall geometric description of a ship. Martec has been studying issues related to the exchange of data between SPMs and LCM tools and has found the STEP protocol appears to provide a robust means to transfer data between SPMs and engineering analysis tools. The main challenge to be addressed in this, and future research efforts, is to develop the "Analysis Model Synthesizer" and "Analysis Management Software" algorithms (see Figure 1.1) that will provide customized data input and output translation for each of the LCM analysis tools.
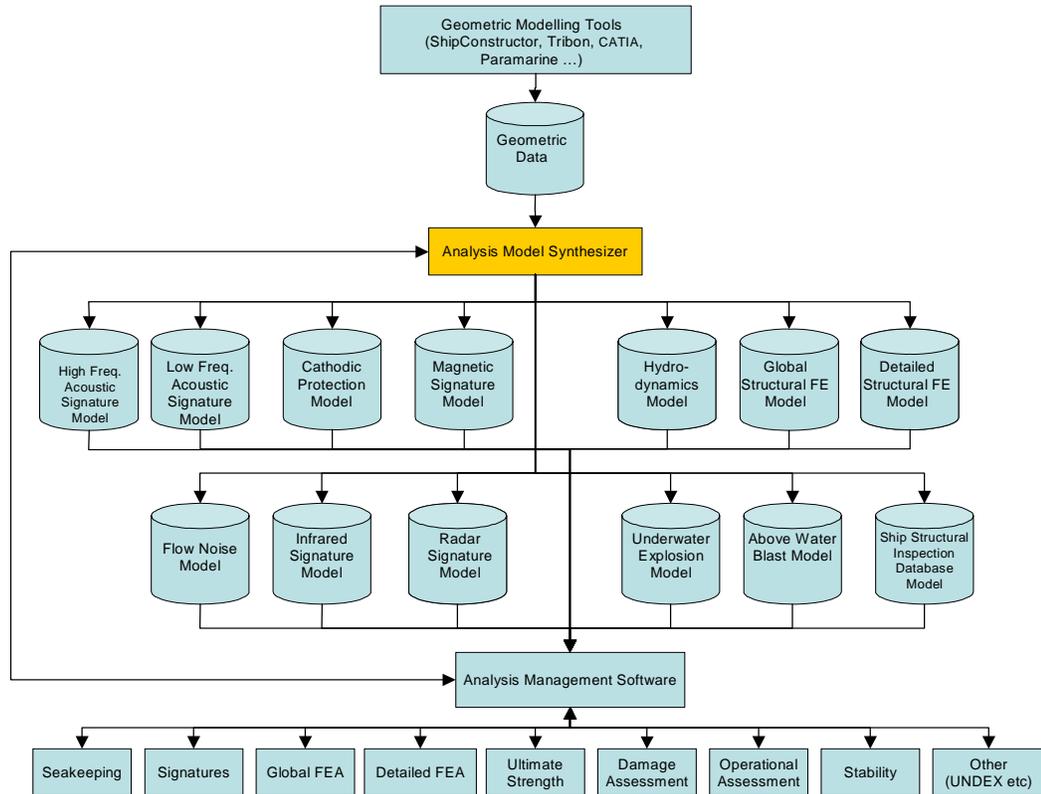
Figure 1.1: Prototype System

1.1 Single Product Management Systems

The tools and techniques used to design ship structures have evolved over the last forty years from producing blueprints on the drafting board to the digital design of today. As computer technology became more powerful and less expensive computer-aided-design (CAD) systems evolved to support the design of complex products. CAD and other related tools empower designers and engineers to create innovative products more quickly and efficiently.

The design process using CAD systems and other tools often results in a multitude of files that describe the elements of a product and how they all fit together. In order to manage this data, software providers developed systems, often referred to as single product model (SPM) management systems. These systems helped engineers manage their evolving designs, and share them with their colleagues within the organization. As design tools grew in capabilities, so too did the desire to support more of the engineering process using data management technologies. SPM systems began to add simple communication and collaboration technologies, such as workflow and notification, to let others know about changes in data of interest, or to include them in the development (or engineering) process. With this increased

emphasis on engineering process came the requirement to manage other types of intellectual assets, such as documents and other files that were part of the development process but developed by tools other than CAD.

During the 1990's, the single product data management systems continued to expand in scope and scale. Figure 1.2 shows a partial list of ship specific SPM vendors. Companies recognized that they could use these systems not just to design their products, but also to manage the product data over the entire lifecycle from concept through deployment. At the same time CAD and computer engineering (CAE) technologies grew in complexity and capabilities.

Less expensive hardware and more powerful tools provided the incentive for many companies to move from 2D CAD to 3D, which is a prerequisite for many analysis techniques like the finite element method (FEM). Once limited to mainframe computers these powerful analysis tools also moved to the desktop putting the full range of CAE at the engineer's fingertips.

Stage	Basic Design		Analysis				Detailed Design	LCM	
Software	Hullform	Basic Desig	Stability	Power	Seakeeping	FEA	Detailed Design	Damage	Operational
Martec - Trident					WaveLoad	Trident FEA			
Aerohydro - Multisurf	X		X						
ARL - Shipconstructor	X	X					X		
Autoship Systems - Autos	X		X	X			X		
Aveva - Tribon	X	X	X		X		X		
BAI - Strand7						X			
Dassault - Catia		X					X		
Defcar Engineering - Defcar	X	X	X				X		
Friendship	X		X						
Formation - Maxsurf	ARL	ARL	X	X	X		ARL		
GRC - Paramarine	X	X	X	X			X	X	
Napa OY - NAPA	X	X	X	X					
Nupas - Cadmatic		X					X		
Proteus - Flagship	X	X	GHS	Navcad	X	X	ARL		
Robert McNeel - Rhino	X								
Sea Solution	X	X	X				X		
Sener Group - Foran	X	X					X		
Vacanti - Prolines	X								

Figure 1.2: Ship SPM Software Vendors

1.2 DND / Martec Lifecycle Management Analysis Tools

Over the past several years, Martec Limited, under contract to DRDC Atlantic, has developed a series of LCM modeling tools encompassing nine of the thirteen analysis disciplines under consideration in the proposed research project (see Table 1.1). Of particular relevance is Martec's involvement in the IST project. The IST (Improved Ship Structures Maintenance Management) Technology Development Program successfully demonstrated the concept of using a CAD-like database of the HALIFAX class along with advanced sea load and structural analysis methods (which include global finite element analysis, detailed finite element analysis, fatigue and ultimate strength analysis) to determine the effects of structural damage on a vessel's ability to undertake intended operations. The IST project, as well as other DND programs such as the Structural Inspection Database (SID) and the TRIDENT program, which is a general purpose ship structural analysis tool recently developed further by Martec to address FELEX issues, provide an extensive set of software tools to address structural LCM issues.

Table 1.1: Analysis/Modeling Capabilities of Interest

Analysis/ Modeling Capability
1. Global structural finite element analysis
2. Detailed structural finite element analysis
3. Hydrodynamic analysis
4. Radar signature
5. Infrared signature
6. Electro-Magnetic signature
7. Cathodic protection
8. Low frequency acoustic signature
9. High frequency acoustic signature
10. Flow noise
11. Underwater explosion analysis
12. Above water blast analysis
13. Ship structural inspection database (SID)

In the discussion that follows a brief summary highlighting Martec's experience in each of these analysis disciplines is provided.

2. Model Data Requirements

2.1 Global Structural FEA

2.1.1 Technical Background

Typically for the creation of the global finite element model the user requires a complete set of the structural drawings for the vessel. The drawings must be reviewed at a macroscopic level with the entire vessel in mind. This is done to enable the engineer to make the necessary decisions to generate a coarse mesh finite element model of the ship. Plate thickness and stiffener scantlings can be obtained from the structural drawings. The mass distribution of the vessel is also required, typically from the vessels weight curve. Numerous weight curves are required for the different loading scenarios that the vessel will experience over the operation of the vessel (e.g. deep departure, operational lightship, design sag and design hog).

As with any finite element analysis, the material properties for the vessel are required. The materials typically seen in ship structures are steel, aluminum and composites.

The structural components that make up a global FEA model drive the fidelity of the model. For example, if the location of a thickness change on the deck is at 100mm away from a bulkhead then, for the global model, the thickness change should be modelled at the bulkhead.

Typically, global models consist of stiffened shell (smeared) elements. The advantage of the stiffened shell element is that the global model will accurately represent the structural response of the ship on a global scale with a very coarse mesh. As computing power increases it is possible to have a global model composed of quadrilateral shell and beam elements instead of stiffened shell elements. The number of nodes and elements would be drastically increased but the model would have a higher level of detail and therefore more accurately represent the structure.

2.1.2 Review of Current Practices

Spreadsheet tools or rule based design allow the designer to look at initial sizing of structural elements at the early design stage. The formulas are based on historical rules. Typically, the Bernoulli-Euler beam theory is used to compute the component of primary stress or deflection due to vertical or lateral hull bending loads.

For global finite element model generation and analysis, the tools used at DRDC Atlantic include ShipMesh, Trident FEA and MAESTRO. To aid in the creation of the FEM, lines of form and deck plans can be imported into the FEA program. Material properties and thickness as well as beam scantlings must be input by the user.

For concept and preliminary design, some of the current software tools in use today are Paramarine, Tribon and the Flagship suite. The data that could be used from the concept design are the hull form and layout of the ship. The data that could be used from the preliminary design would be the hull form, layout and global structural scantlings.

Lloyds RulesCalc could be used early in the design stage to generate the structural scantlings.

CAD systems are used extensively at the production stage of ship design. Some of the popular programs are CADDS5, ShipConstructor, Rhino, Catia, Foran, Autoship and Intergraph. Most CAD systems provide only geometric representation of the structure with no material property data. The material property data is essential for finite element analysis. The Step AP218 is one method to obtain the necessary information. Another is directly through an API. ShipConstructor is developing an API so that systems can directly access geometric, material and descriptive data of the model.

2.1.3   Summary of Data Requirements

The data required for a global finite element analysis are:
- geometry (that is equivalenced to ensure proper connectivity) including section properties,
- material properties,
- mass data, and
- loads

Of these, it is the geometric, mass and material data that will be imported from a LCM database.

Geometric Data

For longitudinal strength analysis of a global finite element model in the preliminary design stage it is necessary to supply geometric and material data for the following structural components:

- All longitudinal elements that are continuous along the ship including
    o decks, longitudinals, girders, bulkheads, hull
- Longitudinal elements that are not continuous should be modelled, paying special attention to the way the discontinuity is modelled.
- Girders (should be modelled with beam elements)
- Stiffeners (should be smeared into the plate)
- Major transverse bulkheads have to be modelled
- Frames (should be modelled with beam elements)
- Pillars
- Floors

Since girders, stiffeners and frames are either incorporated into adjoining plate elements or are modelled with beam elements it follows that centreline locations and section properties are sufficient. Geometric data for all other components would consist of mid-thickness locations and plate thicknesses.

Using the geometric data from the concept and/or preliminary design software will be essential for a global model analysis tool. However, the program should also be able to generate a model of the hull shape from the lines of form.

Section Properties & Material Data

Plate thickness, stiffener scantlings and structural material properties are all required for the global finite element analysis.

The most basic structural material data includes Young's modulus and Poisson's Ratio. Depending on the type of analysis, additional material data may be required. This could include: density, yield stress, non-linear structural properties, fatigue properties.

Mass Data

An accurate representation of the weight of the ship is required for global structural analysis. The most efficient approach to obtain the correct weight and distribution is to use a weight curve. The mass of items such as engines and equipment that weigh over 10 tonnes should be represented separately and located at the correct position in the global model.

2.2 Detailed Structural FEA

2.2.1 Technical Background

Creating a finite element model for a detailed structural analysis usually involves creating very refined and complicated finite element models of a local area of interest. For example, the state of stress at a specific location of a specific structure member under a specific loading condition might be required. Alternately, the fatigue life of a particular connection detail might be of concern. The complexity of the model is dependant on the level of detail that is required for a particular analysis. Complex meshes require sophisticated meshing algorithms, such as the paving algorithms that have been developed at Martec as part of the Trident FEA and IST tools that are used by DRDC. As with the global structural FEA, plate thickness, stiffener scantlings and material properties are all required for detailed finite element analyses.

Once a detailed finite element model is complete, an accurate description of the applied loads must be added. Loading on a ship is very complex. When a detailed structural model of a ship component is confined to that portion of the ship that is in the region of the component of interest, manual creation of accurate loads/boundary conditions can be extremely difficult. To overcome this difficulty a "top down" approach is often employed. This approach to detailed FE analyses actually involves two analyses. A global model of the ship is created and known loads are applied to the global model. Calculated (accurate) displacements from the global model are then applied to the boundaries of a detailed finite element model. This process allows the user to conduct a local finite element analysis with the confidence that the loads applied to the detailed model are accurate.

FE models can be made in a manual fashion, that is, without the benefit of imported geometries and automatic mesh generation tools. This takes a lot of user intervention and is typically slower when compared to automatic mesh generation techniques. Hence, for an all encompassing LCM suite a detailed structural analysis tool would benefit from a link to the geometric modelling tools which would make it possible to import a geometric description of structures. The geometry should be in STEP, IGES or another CAD format. Once the geometry has been imported then the automatic meshing will create finite element meshes. The level of detail of the finite element mesh will be dependant on the detail of the geometry as well as the type of analysis.

As shown in the following figures, detailed models might require locations of each part of a beam, girder or stiffener. While it is sometimes possible to infer the locations of web and flange corners from section properties, some additional information might be required. This could include connection details that indicate how the ends of members are modified to accommodate adjoining members.

The Figure 2.1 shows an example of a finite element mesh that was generated for a structural strength analysis of the Halifax Class flight deck.
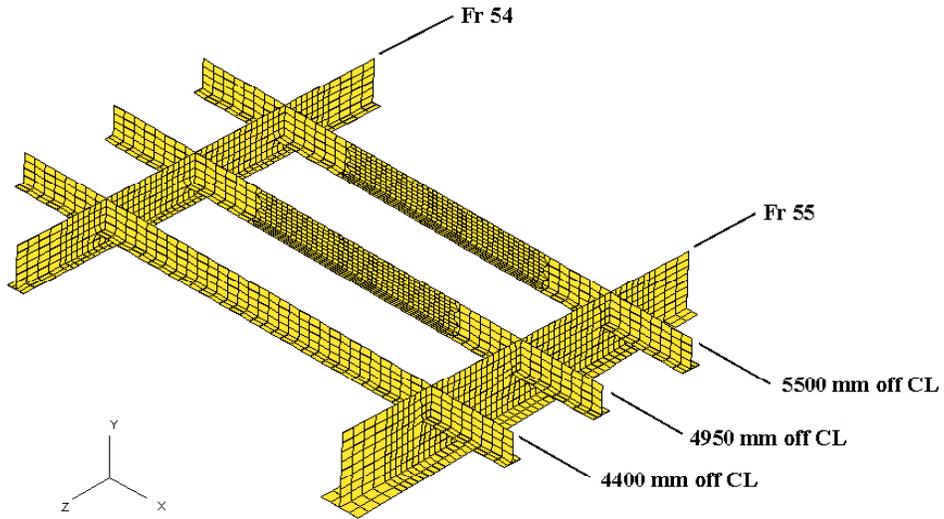
Figure 2.1: Detailed model of CPF flight deck

Figures 2.2 and 2.3 show two highly refined meshes that were created for fatigue and fracture analyses. The complicated meshes were created by way of the IST tool, which includes a paving algorithm.
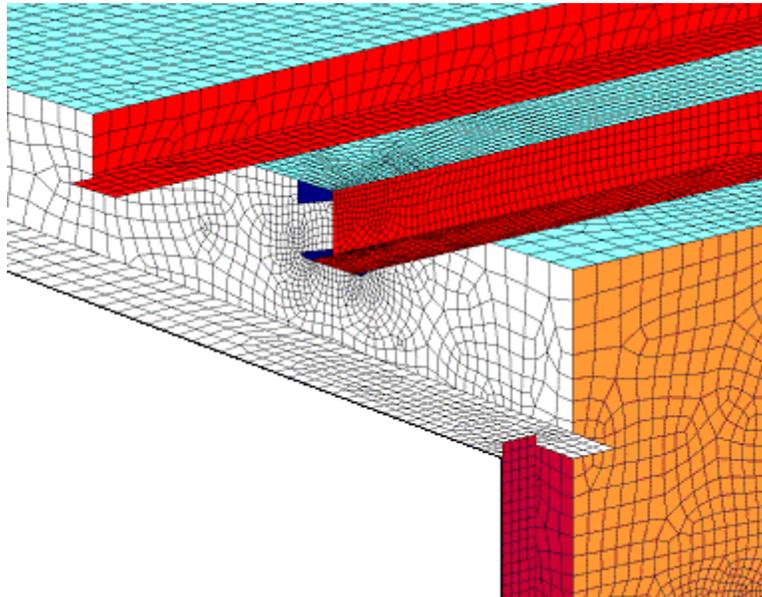
Figure 2.2: Second example of mesh for detailed structural analysis
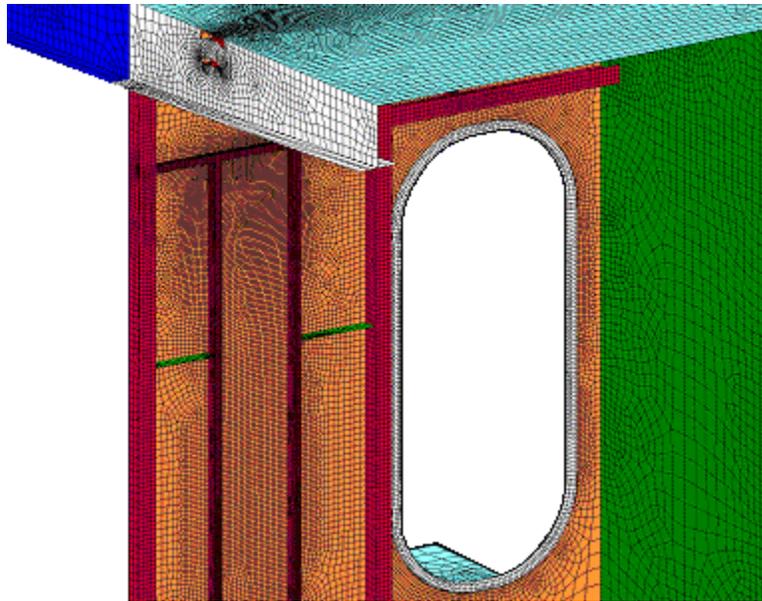
Figure 2.3: Third example of mesh for detailed structural analysis

2.2.2   Review of Current Practices

The tools employed by, or developed with funding from, DRDC Atlantic for detailed finite element analysis are:

- Trident suite including Trident FEA,
- Improved Ship Structures Maintenance Management Software Tool (IST),
- SubSAS and
- Ansys.

Some other FEA software products are:

- Nastran
- Marc
- Patran
- Dyna3D
- Sesam
- Adina
- Abaqus
- ALGOR
- Femap
- Cosmos

2.2.3   Summary of Data Required

Data requirements for a detailed FE analysis are similar to those for a global FE analysis.

Detailed Geometric Data

- equivalenced to ensure proper connectivity

The level of detail required of a structural FE model will depend on the specified analysis. For example, a fatigue and fracture analysis will require a more detailed mesh than a structural stress analysis that determines the structural integrity of a deck. Therefore the fidelity of a model must be sufficiently flexible to accommodate the diverse requirements of various types of structural analyses.

Section Properties & Material Data

- as per global analysis

Mass data

- as per global analysis

Boundary Conditions

- not from LCM data,
- from a top-down (global FEA) analysis as well as any internal BC's

2.3　Hydrodynamics

2.3.1　Technical Background

Hydrodynamic analyses, which involve the calculation of hydrodynamic forces on a ship and ship motion in a wave environment, can be categorized into four types:
- ship stability which includes static and dynamic stability analysis;
- the performance of ship speed which includes the ship resistance analysis and ship propulsion analysis;
- the performance of seakeeping which predicts the ship motions in waves; and
- the performance of the ship maneuverability which includes coursekeeping, maneuvering and speed changing.

Boundary elements and CFD/RANS are the two main tools used in numerical hydrodynamic analysis. The boundary element method is applied to situations in which the effects of viscous flow can be ignored, such as seakeeping analysis, wave resistance analysis, propulsion analysis and maneuvering analysis. On the other hand, the RANS method is most suitable for resistance analyses, some propulsion models and maneuvering models, where viscous flow is significant. Dynamic ship stability analysis is usually coupled with the analysis of maneuvering and seakeeping.

In the boundary element method the boundaries of a fluid domain are discretized into a mesh of panels. These boundaries can include: the wetted surface of a structure, such as the ship hull surface or the surface of the propeller blades and hub, and parts of other boundaries such as the free surface and/or sea bottom. The unknown velocity potential or source strength of certain types of singularity on each panel are then determined by solving the governing equation, usually the Laplace equation with the body surface condition, free surface condition and radiation condition. From the computed velocity potential the hydrodynamic pressure on each panel is determined by first calculating the flow speed which is then input into Bernoulli's equation. The hydrodynamic forces and ship motion can then be estimated. Some empirical formulas are used with the boundary element analysis to include viscous effects.

In the RANS method, the whole fluid domain is discretized into a number of 3D grids. The unknown flow velocity and pressure at each grid is determined by solving the Reynolds-Averaged Navier-Stokes equation together with the boundary conditions and some turbulence model. The forces and motions can be estimated after the pressure is solved.

2.3.2　Current Practice and Tool Sets

DRDC Atlantic primarily uses PRECAL and ShipMo for hydrodynamic analysis. In addition, DRDC Atlantic has contributed to the development of Trident FD-Waveload and Trident TD-Waveload. These programs, which have been developed by Martec over the last six years, are three-dimensional boundary element software programs that are part of a hydrodynamics suite. Trident FD-Waveload is a frequency domain code and Trident TD-Waveload is a time domain code. These software tools, together with other ship hydrodynamic computer

programs such as PRECAL and ShipMo have been used by Martec to analyze seakeeping performance and to compute wave-induced loads for a variety of ship structures, including the Halifax class frigate [70-73].

2.3.3   Summary of Data Requirements

The following information is required for the hydrodynamic analysis of a displacement type ship. For other types of ships, such as hydrofoil vessels or air-supported crafts, different data will be required.

<u>Ship Geometry and Weight Distribution</u>

Basic ship data: First, and foremost, the geometry of ship hull surface, without appendages, rudder and so on is modelled. This surface description could take the form of a NURBS expression, or a set of meshes in standard boundary element format, or an offset table. If the hull geometry is defined by an offset table then three types of projection lines (body-plan lines, water-plan lines and buttock-plan lines), must be provided together with necessary additional lines such as the chine line and deck edge line. The points listed in the table should have the characteristic property like FAIR or KUNCLE. Skin roughness is needed for the fraction resistance estimation. In addition, the following particulars are needed

- Length Overall
- Length between perpendiculars (L)
- Beam (B)
- Midships draft (T)
- Trim
- Volume displacement (∇)
- Displacement
- Longitudinal location of the center of gravity in station
- Center of gravity above keel
- Longitudinal metacentre height
- Transverse metacentre height
- Wetted hull surface area
- Water plane area (Awp)
- Radius of gyration in roll
- Radius of gyration in pitch
- Radius of gyration in yaw
- Cross mass inertia moment between x- and y-axis
- Cross mass inertia moment between y- and z-axis
- Cross mass inertia moment between z- and x-axis
- Block coefficient ($Cb=\nabla/(L*B*T)$)
- Midship coefficient (Cm=Immersed area of midship section)/(B*T))
- Water plane coefficient (Cwp=Awp/(L*B))
- Prismatic coefficient (Cb/Cm)
- Vertical prismatic coefficient (Cb/Cwp)

Hull Section Parameters

Sectional data, based on station sections or frame sections, are also needed. At each section the required information includes a body-plan line as well as the following section parameters.

- Section beam (b)
- Section draft (t)
- Section area (S)
- Section mass
- Center of section gravity above keel
- Section radius of gyration in roll
- Section radius of gyration in pitch
- Section radius of gyration in yaw
- Section coefficient (Cs= S/(b*t))
- Section length
- Area of wetted hull surface

Appendages

- **Bilge Keel:** Geometric bilge information includes: root line coordinates (x_i, y_i, z_i) defining the intersection between the bilge keel and the ship hull; tip line coordinates (x_i, y_i, z_i); the section shape; bilge keel height; bilge keel length; and the bilge keel depression angle.
- **Fins**: Fin section shape; fin span; fin chord; fin thickness; fin root submergence; bilge radius at fin location; fin depression angle; distance of fin centre of pressure from fin root; longitudinal location; lateral offset from the ship centerline; vertical position from keel plane; mechanical limitation of attack angle.
- **Skeg information:** Skegs can be defined by a set of the panels if it is not included in the hull surface geometry part.
- **Rudder system:** Rudder geometric information includes section shape; rudder span; rudder thickness; rudder chord information including rudder flap chord and rudder mean chord; ratio between flap angle and mechanical angle; numerical factor related to flaps if the rudder has flaps; bilge radius at rudder location; rudder depression angle; distance of rudder centre of pressure from rudder root; longitudinal location; lateral offset from the ship centerline; vertical position from keel plane.
- **Propeller system:** The geometry of the propeller, including the blades and hub should be defined by a NURBS expression of a set of panels. The geometry of the nozzles part should also be defined in a similar way if the system is a ducted type. Thrust, RPM, wake factor, location of the centre of the propeller disk and turning direction should be provided. Following parameters are needed as well: number of blades, diameter, pitch, blade thickness ratio, pitch angle, disk area, developed area of blades outside hub, developed area ratio, projected area of blades outside hub, projected area ratio, blade width ratio, mean width ratio.

The geometry (shape) of the ship hull and appendages should be available from the database and should be sufficiently detailed to provide shapes to a scale of roughly 1 to 2 meters.

Environmental Parameters

Required environmental parameters for a hydrodynamic analysis include:
- Ship speed, and engine working data,
- Water depth or bathymetry data,
- Wind speed and wind direction,
- Current speed and direction,
- Wave statistic parameters such as the type of the random sea, the significant wave height and peak or averaged wave period, and the principal wave direction of the operation area for a irregular sea analysis,
- Measured wave spectrum of the operation area for an irregular sea analysis, or the wave condition: wave frequency, wave direction and wave height for a regular wave case analysis.

Wave statistics data should be available from AES hindcast database, while the measured wave spectrum could be obtained from sea trials. The bathymetry data is available from some database such as ETOPO2.

2.4   Radar Signature

2.4.1   Technical Background

Radar and Radar Cross Section (RCS)

Radar (RAdio Detection And Ranging) is a method for detecting the position and velocity of objects by means of very high frequency radio pulses. A radio pulse sent to an object is partly transmitted and partly reflected. The direction of the reflected pulse and the amount of time it takes to return to the transmitter are used to determine position of the object. Radar imaging works very much like a flash camera in that it provides its own light to illuminate an area on the ground and take a snapshot picture, but at radio wavelengths. Instead of a camera lens and film, radar uses an antenna and digital computer tapes to record its images. In a radar image, one sees only the light that was reflected back towards the radar antenna [5].

Radar cross section (RCS) is the measure of a target's ability to reflect radar signals in the direction of the radar receiver, i.e. it is a measure of the ratio of backscatter power per steradian (unit solid angle) in the direction of the radar (from the target) to the power density that is intercepted by the target [10].

Radar antenna typically transmit and receive pulses at frequencies in the range of 300MHz to 30GHz, which is within the frequency limits of the radio and microwaves in the electromagnetic spectrum as shown in Table 2.1 [5]. A radar system sends out up to 1500 high- power pulses per second that are transmitted toward the target or imaging area, with each pulse having a pulse duration *(pulse width)* of typically 10-50 μs, and covering a small band of frequencies (10-200 MHz), centered on the frequency selected for the radar. At the Earth's surface, the energy in the radar pulse is scattered in all directions, with some reflected back toward the antenna. This backscatter returns to the radar as a weaker radar echo and is received by the antenna in a specific polarization (horizontal or vertical, not necessarily the same as the transmitted pulse). These echoes are converted to digital data and passed to a data recorder for later processing and display as an image. Since a radar pulse travels at the speed of light, the range of the reflecting object is given by the product of the speed of light and the measured time for the roundtrip of a particular pulse. The chosen pulse bandwidth determines the resolution in the range (cross-track) direction. Higher bandwidth means finer resolution in this dimension [5]. Figure 2.4 illustrates the concept of radar and RCS.

Table 2.1: Approximate wavelength, frequency, and energy limits of the various regions of the electromagnetic spectrum [9]

	Wavelength (m)	Frequency (Hz)	Energy (J)
Radio	$> 1 \times 10^{-1}$	$< 3 \times 10^{9}$	$< 2 \times 10^{-24}$
Microwave	1×10^{-3} - 1×10^{-1}	3×10^{9} - 3×10^{11}	2×10^{-24} - 2×10^{-22}
Infrared	7×10^{-7} - 1×10^{-3}	3×10^{11} - 4×10^{14}	2×10^{-22} - 3×10^{-19}
Optical	4×10^{-7} - 7×10^{-7}	4×10^{14} - 7.5×10^{14}	3×10^{-19} - 5×10^{-19}
UV	1×10^{-8} - 4×10^{-7}	7.5×10^{14} - 3×10^{16}	5×10^{-19} - 2×10^{-17}
X-ray	1×10^{-11} - 1×10^{-8}	3×10^{16} - 3×10^{19}	2×10^{-17} - 2×10^{-14}
Gamma-ray	$< 1 \times 10^{-11}$	$> 3 \times 10^{19}$	$> 2 \times 10^{-14}$
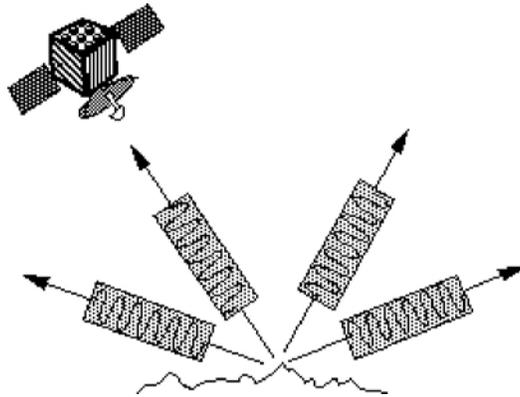
Figure 2.4: Concept of radar and radar cross section [5]

The RCS is integral to the development of radar stealth technology, particularly in applications involving aircraft and ballistic missiles. RCS data for current military aircraft are almost always highly classified.

Measurement and Analysis of Radar Cross Section (RCS)

Measurement of the RCS of an object is usually performed at a radar reflectivity range or scattering range, which could be an outdoor range or an anechoic chamber. In an outdoor range the object or target is positioned on a pylon some distance down-range from the transmitters. Such a range eliminates the need for placing radar absorbers behind the target, however multi-path effects due to the ground must be mitigated. In an anechoic chamber, the target is placed on a rotating pillar in the center, and the walls, floors and ceiling are covered by stacks of radar absorbing material. These absorbers prevent corruption of the measurement due to reflections. A compact range is an anechoic chamber with a reflector to simulate far field conditions [16] .

Quantitatively, the RCS is an effective surface area that intercepts the incident wave and that scatters the energy isotropically in space. A simple method for computing RCS is based on the radar range equation, which is given by [2]:

$$P_r = \frac{P_t G_t}{4\pi R^2} \frac{\sigma}{4\pi R^2} \frac{G_r \lambda^2}{4\pi} \frac{1}{L} \qquad (2.1)$$

which, on rearrangement gives the RCS as

$$\sigma = \frac{P_r(4\pi)^3 R^4 L}{P_t G_t G_r \lambda^2}$$

(2.2)

where σ is the RCS of the target;
      P_t is the transmitted power,
      P_r is the received (or returned) power,
      G_t is the gain of the transmitting antenna;
      G_r is the gain of the receiving antenna;
      λ is the wavelength of the incident radar;
      R is the range of the target; and
      L is a numerical factor to account for losses.

A comparative measurement with a target of known RCS is used to obtain the actual target RCS, such that the actual RCS, is given by

$$\sigma_{tar} = \sigma_{cal} \frac{(P_r)_{tar} R_{tar}^4}{(P_r)_{cal} R_{cal}^4}$$

(2.3)

Expressions for calculating RCS for typical target shapes are shown in Figure 2.5. The RCS data processing system (RCSDSP) used by DRDC Ottawa is based on the Equation 2.3. [2]
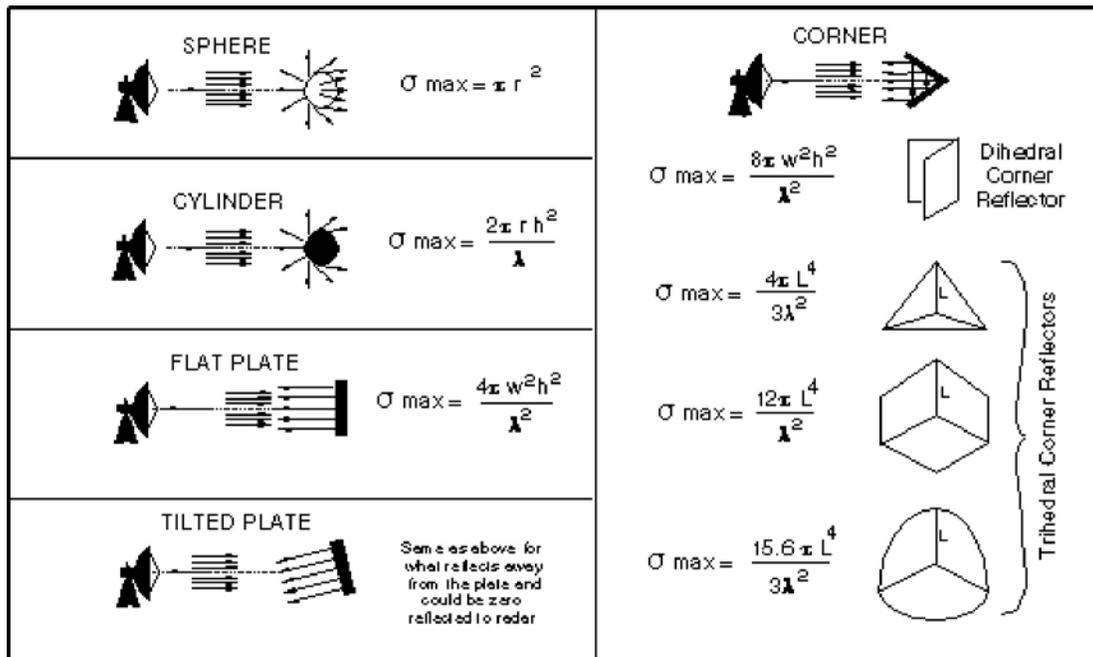
Figure 2.5: RCS for Selected Target Shapes [10]

The above expressions provide a simple method of computing the RCS of objects, using radar measurements. However, in the design phase it is desirable to predict how the RCS of an actual object would look like before fabrication, in order to optimize the radar stealth performance of the structure/object. This usually involves solving Maxwell's equations through numerical algorithms or computational electromagnetics. RCS prediction programs are often run on large supercomputers and employ high-resolution CAD models of real radar targets.

Solution of Maxwell's equation for RCS prediction should be performed within the high frequency (HF) electromagnetics range, because radar signature involves the generation and propagation of electromagnetic energy in free space, together with its interaction with dielectric media, and because the wavelengths are similar or smaller than the geometric dimensions of the structure. Commonly used HF approximations for modeling RCS include the following:

- Geometric Optics (GO): which relates RCS directly to the local radii of curvature at normal incidence, and is not suitable for flat or singly curved surfaces;
- Physical Optics (PO): which approximates the induced surface fields and integrates to obtain the far scattered fields. This method is suitable for flat and polygonal plates and can account for multiple scattering up to triple reflections;
- Geometric theory of diffraction (GTD): designed to handle edge diffraction effects
- Method of equivalent currents (MEC): which extends the applicability of diffraction theories such as GTD. It uses the fact that a finite current distribution, when summed in a radiation, yields a finite result for the far diffraction field [8]; and
- Purely numerical methods such as boundary element methods (BEM), finite difference time domain (FDTD), and finite element methods, that are limited by computer performance to longer wavelengths or smaller features.

Radar Stealth Technology

The determination of RCS of major scattering centers on naval vessels and achieving reduction of RCS is of great tactical significance to the navy. Since radar can be used to detect the presence of vessels even at great distances, it is desirable to reduce the RCS of the vessel, in order to avoid detection. The smaller the RCS, the easier it is for a vessel to evade radar detection. Radar reduction (or stealth) technologies currently used include the following:

- Purpose shaping: which is an RCS reduction technique in which the shape of the target's reflecting surfaces is designed such that they reflect energy away from the source. This is a passive radar reduction technique, similar to the design of the surface faceting on the F-117 Nighthawk stealth fighter.
- Active Cancellation: which involves the target vessel generating a radar signal equal in intensity but opposite in phase to the predicted reflection of an incident radar signal (similarly to noise canceling ear phones); and
- Radar absorbing materials (RAM): which involves the use of radar absorbing material (RAM) either in the original construction or as an addition to highly reflective surfaces. Types of RAM include resonant, non-resonant magnetic and non-resonant large volume [16].

DRDC Atlantic, with the support of Technology Investment Funding has been leading a project on the development of Radar absorbing material, RAM, and the reduction of Radar cross section, RCS. Part of this effort involved investigations into the applicability of polyaniline for RAM [6].

DRDC Ottawa with Concordia University have been working on a software program called RPO [17] to predict the RCS of a ship, based on its structure and position in relation to the radar antenna. The software code gives a colour indication of where hotspots exist in a ship's structure (see Figure 2.6). This information can be used during ship design, for the minimization of the RCS. It can also be used to highlight where RAM should be applied to reduce the RCS. The code has the capability to recalculate the RCS when RAM patches have been applied to hotspot areas.
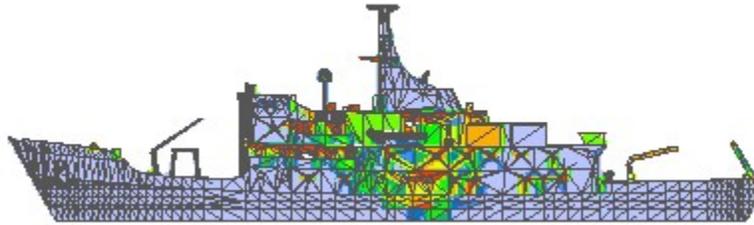
Figure 2.6: Typical plot illustrating RCS hot spots (DRDC Atlantic, 2005)

According to Kashyap [7], DND currently has not decided on a dedicated RCS analysis tool. However, some DND RCS software development efforts have been reported in the literature [2, 8]. Furthermore, there are several commercial RCS analysis tools that are available on the market. Brief highlights of some of these software tools are presented below. It should be noted that the information provided here is based mainly on software vendor literature and publications available in the public domain. No independent evaluation of the software products was performed in this study.

2.4.2   Tool Sets

RCSDPS

RCSDPS (acronym for radar cross section data processing software) is a software tool developed by Atlantis Scientific Inc. [2], for DRDC Ottawa. The software is written in MATLAB and is designed to process raw radar data obtained by the RCS Data Acquisition System (RCSDAS). It also has the capability to process high range resolution (HRR) data, which is used to determine the relative locations of major scatterers of targets. The RCS computations are based on Equation 2.3 above. Calibration devices used include a metallic sphere tethered to a weather balloon; a small corner reflector; and the DRDC Ottawa medium and large range corner reflectors, which were measured at the David Florida Laboratory.

Ligali [8] has also discussed a DND and RCS analysis tool comprising of three components including (1) an AutoCAD geometric specification module; (2) a MATLAB RCS calculation module; and (3) an EXCEL tabular output component. For the MATLAB RCS computations, PO methods are used for modeling large complex bodies where the returns are dominated by

specular (reflection) effects; whereas the MEC method is used to correct results for simple bodies where diffraction effects are significant.

<u>Epsilon</u>

Epsilon™ is a software tool designed to predict the Radar Cross Section (RCS) of a target directly from its geometrical description. It is developed by Roke Manor Research Limited, Hampshire, UK. The fundamental approach of Epsilon™ is to use surface space CAD descriptions of geometry from which the radar cross section can be predicted. Once the radar cross section has been predicted, Epsilon™ can then calculate the radar signature or radar image. The CAD descriptions can be sourced from a variety of locations such as: proprietary CAD, line drawings, Internet sources, photographs or models. The Epsilon™ license includes CAD translators to convert to the required format for Epsilon™ use. Figure 2.7 shows a flow chart of the Epsilon™ CD generation process. The RCS analysis approaches provided by Epsilon™ include:

- Physical Optics (PO): Epsilon™ implements the Kirchoff Physical Optics approximation to evaluate the boundary condition and applies a Stratton-Chu integration over the whole body to evaluate the scattered field strength at any point in space. This is the most fundamental and flexible form of Physical Optics.
- Physical Theory of Diffraction (PTD): implemented as the Mitzner Incremental Length Diffraction Coefficients (ILDC), and when combined with the PO solution it provides a solution sometimes referred to as Geometric Theory of diffraction (GTD).
- Geometrical Optics (GO): implemented as a fully automated ray tracer, which when combined with PO gives a solution sometimes referred to as GOPO. This is essential for calculating the multiple scattering from targets. The number of interactions is unconstrained which enables complex scattering structures, such as ducts, to be calculated implicitly without any special user attention; and
- Diffuse Ray Optics (DRO): a sophistication of Geometrical Optics and provides more accurate results for multiple scattering from curved surfaces.
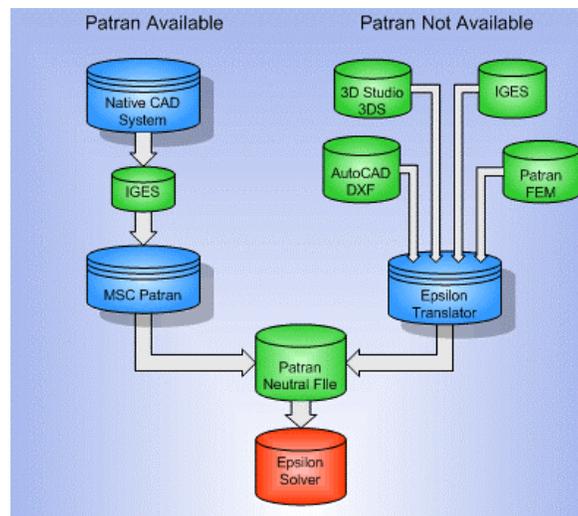
Figure 2.7: Epsilon CAD Generation (Roke Manor Research, 2006)

<u>CADRCS</u>

GRC with CSS of Denmark provide a seamless Paramarine connectivity in the field of RCS. The method of RCS analysis is based on CAD geometry and developed by CSS. This integrated modeling and RCS analysis capability gives a baseline capability for assessing the RCS of ships. CADRCS is a special encodement of the PO approach including shadowed areas through a combination of graphical and numerical results a ship can be rapidly analyzed from a CAD definition to identify the RCS hotspots. Solutions to eradicate hotspots can be determined either using a simulated RAM coverage or reshaping the structure.

Paramarine generates the facet body data used by CADRCS. In the model shown in Figure 2.8 the geometric facet data was imported from a NATO format file. Paramarine can create CAD elements (and may be used to import other CAD geometry as STL, DXF, STEP, IGES or NATO format) such as sheet bodies from points and place these sheets as cover for a corner reflector identified and set their coefficient of reflection to a low value representative of a RAM characteristic. Validation studies have been performed through comparisons with ship measurements and experience at the Danish Research Establishment (DDRE).
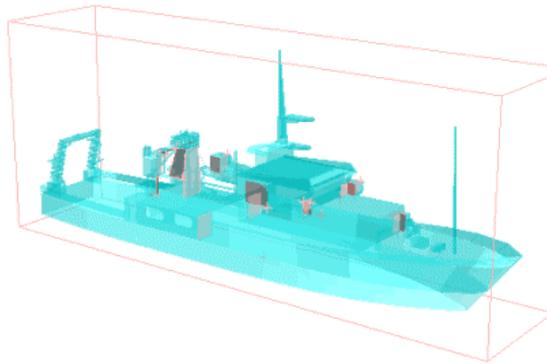
Figure 2.8: CADRCS CAD Model of a Ship Structure (CSS, 2006)

XGTD

XGTD is a general purpose ray-based electromagnetic analysis tool suitable for radiation, antenna, and EMC applications. It is developed by Remcom, College Station, PA, USA. XGTD combines geometrical theory of diffraction (GTD), uniform theory diffraction (UTD), and Surface Rays to include all important diffraction mechanisms present in high frequency analysis of devices in the vicinity of complicated objects. The software is aimed toward the analysis of antennas on vehicles or aircraft, but is also suitable for anechoic chamber simulations. The software has capabilities for importing CAD files of complex objects from NSMA, Odyssey, MSI Planet, and XFDTD files. Output from the calculation engine includes near-zone fields, far-zone antenna patterns and antenna coupling and interference measures. Display of the possible ray paths, color-coded to indicate signal strength, is possible in addition to planar field displays of field strength. The full 3D propagation model is based on a hybrid shooting and bouncing ray SBR/GTD approach developed by Remcom. The SBR method is employed at the start of the calculation to determine the geometrical ray paths within the project geometry. The SBR method has been implemented with robust ray tracing techniques that impose few limitations on the complexity of geometry features. Once the

propagation paths have been found, the amplitudes are evaluated using the GTD. Figure 2.9 shows typical XGTD power ray paths for a corner reflector.
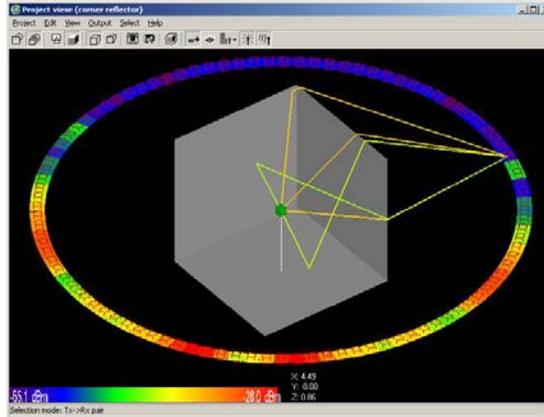
Figure 2.9: Received power and ray paths for the corner reflector composed of metal

plates.

XPatch

Xpatch® is a set of prediction codes and analysis tools that use the shooting-and-bouncing ray (SBR) method to predict realistic far-field and near-field radar signatures for 3D target models. It is developed by SAIC, San Diego, CA, USA. The Xpatch toolset is used by the Air Force Research Laboratory and Defense Advanced Research Projects Agency (DARPA) for multiple radar simulation programs. SAIC states that there are over 421 organizations across the USA in both industrial and government applications using Xpatch to produce and analyze scattering data for realistic aircraft, missiles, ships, spacecraft, and ground vehicles. They include multiple government organizations and major aerospace firms such as Lockheed Martin, Northrop Grumman, Boeing, Sikorsky Aircraft, Raytheon, and TRW. The main features of Xpatch include the following:

- The Xpatch code suite was rewritten in a C++ object-oriented framework combining the Xpatch 2.4 versions of XpatchF and XpatchT into a single product. Xpatch 4.6 enhancements include:
- Near-field capabilities to simulate missile fuzing applications, turntable, ground based radar/missile fly-by, range gates, and near-field SAR support
- Multiple IGES entities, scattering centers, and hybrid capabilities support.
- FISC 1.4, a method-of-moments solver using the breakthrough multilevel fast multipole algorithm (MLFMA) fast matrix solver, originally developed at the University of Illinois.
- TEMPUS 1.0., a finite-volume time-domain (FVTD) electromagnetics solver from HyperComp, Inc., for scalable performance on parallel platforms including IBM-SP, Cray T3E, SGI, and PC clusters. More information is available at http://www.hypercomp.net.
- Full (XpatchF style) materials support for time-domain as well as frequency-domain runs

- Ability to perform signature analysis in one of three different modes: radar cross-section (RCS), range profile, or SAR
- Maintenance of a large database of both measured radar and Xpatch-generated synthetic radar signature data

RadBase

RadBase, developed by Surface Optics Corporation (SOC), San Diego, CA, is a commercial off-the-shelf (COTS) software system for generating Radar Cross Section (RCS) and Amplitude and Phase data for both complex targets and cultural features. RadBase is a Java-based application, allowing it to run on Windows 95®/98®/ NT® and Unix® platforms. RadBase reads an STK(r) .mdl file directly. The output of RadBase is a RCS file that plugs directly into STK/Radar. The user can also develop RCS databases that plug directly into MultiGen-Paradigm, Inc.'s, RadarWorks(tm) product. Other highlights of the software include:
- the ability to model complex physical phenomena including multiple bouncing and edge effects, and
- support of many 3-D model formats including STK (mdl), OpenFlight(tm), Object(obj) and Demaco (Xpatch) formats.

SOC (2006) state that the code has been validated against a range measurements and the Xpatch software system.

Lucernhammer

Lucernhammer is a collection of software for the calculation of electromagnetic (EM) signatures and RCS. It is developed by Tripoint Industries, Inc., Harvest, AL, USA. The Lucernhammer suite is comprised of the following software tools [15]:
- Lucernhammer MT: High-frequency RCS solver tool. Uses Physical Optics (PO), Physical Theory of Diffraction (PTD), Shooting and Bouncing Ray (SBR) methods. Similar to Xpatch, compatible with Xpatch facet and edge files. Geometric input includes high-resolution triangle meshes of arbitrarily shaped objects.
- Serenity: Low-frequency RCS solver tool. Uses three-dimensional Method of Moments (MoM) technique with EFIE/MFIE/CFIE integral equations and RWG basis functions. Allows a traditional full-matrix approach and an implementation of the Multilevel Fast Multipole Algorithm (MLFMA).
- Galaxy: Low-frequency RCS solver tool. Uses Body-of-Revolution Method of Moments (MoM-BoR) technique with EFIE/MFIE/CFIE integral equations and triangular rooftop basis functions. Suitable for simulation of targets that can be represented as rotationally symmetric objects, such as reentry vehicles and tanks. Also suitable for generating RCS of objects to compare to other codes, such as spheres, ellipsoids, cylinders, frustums, etc.
- Menelaus 3D: transformation and manipulation tools for facet, edge, ILDC, BOR and point scatterer geometry files.
- Fieldian: signature, field and RCS file processing tool.
- Sapphire: Inverse SAR (ISAR) Imaging and visualization tool.
- Emerald: OpenGL geometry model/Serenity surface current viewer

The Lucernhammer code suite is designed to be compatible with the Xpatch/CAD facet geometry file. It contains tools to easily convert other files such as 3D Studio (.3ds), stereolithography (.stl) and raw triangles (.raw) to the native triangular facet file (.facet). The software vendors recommend the use of McNeil and Associates' Rhinoceros 3D for all surface modeling and export. Rhinoceros has the capability and precision to create highly detailed 3D surface geometry suitable for radar cross section simulation and will also export many file formats easily converted by the Lucernhammer tool suite to facet files.

<u>ANSYS EMAG</u>

The popular ANSYS finite element suite has a high frequency electromagnetic computational (EMAG) capability that is suitable for performing RCS analysis.

2.4.3　Summary of Data Requirements

<u>Geometric Properties</u>
- 3-D configurations of the hull, superstructure, mast, and appendages such as equipment, as sonar dome, propeller shafts, brackets, rudders, etc

<u>Material Properties</u>
- Material type, thickness, permittivity, conductivity, permeability

<u>Others</u>
- Source power, frequency, location, threshold field strength

2.5 Infrared Signature

2.5.1   Technical Background

Infrared (IR) signatures belong to that part of the electromagnetic spectrum with longer wavelengths than light but shorter than radio or microwaves (that is wavelengths of 0.7 µm to 1 mm or frequencies of 300 GHz to 400 THz). The term means *below red,* derived from the Latin word *infra* (below). Red is the colour of visible light with the longest wavelength. IR is often subdivided into several regions, although the boundaries and terms are not necessarily defined precisely across various industries [26]:

- near infrared NIR, IR-A, 0.7 – 1.4 µm in wavelength, defined by the water absorption, and commonly used in fiber optic telecommunication because of low attenuation losses in the SiO_2 glass medium.
- short wavelength (shortwave) IR SWIR, IR-B, 1.4 –3 µm, water absorption increases significantly at 1.45 µm
- mid wavelength IR MWIR, IR-C, also intermediate-IR (IIR), 3–8 µm
- long wavelength IR LWIR, IR-C, 8–15 µm)
- far infrared FIR, 15–1000 µm

Infrared radiation is often linked to heat, since objects at room temperature will emit radiation mostly concentrated in the mid-infrared band. The concept of black bodies is used in association with IR radiation. A black body is an object that absorbs all electromagnetic radiation that falls onto it. No radiation passes through it and none is reflected. However, despite the name, black bodies are not actually black as they radiate energy as well. The amount and type of electromagnetic radiation they give off is directly related to their temperature. Black bodies below about 700 K produce very little radiation at visible wavelengths and appear black. Black bodies above this temperature however, start to produce radiation at visible wavelengths starting at red, going through orange, yellow and white before ending up at blue as the temperature increases [27].

IR radiation was discovered in 1800 but its application is still limited in comparison with the radio/radar wave, which was discovered in 1888. However, recently, the application areas of IR signature have gradually been expanding. Some of these applications include [26]:

- Night vision: Infrared is used in night vision equipment, when there is insufficient visible light to see an object. The radiation is detected and turned into an image on a screen, hotter objects showing up in different shades than cooler objects, enabling the police and military to acquire thermally significant targets, such as human beings and automobiles.
- Thermography: Infrared radiation can be used to remotely determine the temperature of objects (if the emissivity is known).
- Heating: Infrared radiation is used in IR saunas to heat the sauna's occupants, and to remove ice from the wings of aircraft (de-icing). It is also gaining popularity as a method of heating asphalt pavements in place during new construction or in repair of damaged asphalt.
- Communication: IR data transmission is also employed in short-range communication among computer peripherals and personal digital assistants (PDA). Infrared lasers are used to provide the light for optical fibre communications systems. Infrared light with a wavelength around 1330 nm (least dispersion) or 1550 nm (best transmission) are the best

choices for standard silica fibres. Infrared is the most common way for remote controls to command appliances.

Of particular interest to this study is the application of IR signature employed by the military for the IR guided missile for detecting the radiated signature from naval ships and the air fighter vessels. As a result, IR signature management has now become important for modern surface warships, and the use of IR design tools to enable ship designers to manage the IR characteristics of the vessel is essential. Analysis of IR signatures enables military commanders to evaluate their vulnerability to IR threats. The analysis addresses the perception of objects by IR sensors, by measuring the radiation emitted by targets and backgrounds, with the parameters of interest usually being the source radiance, intensity and temperature [21]. A ship platform IR signature is composed of several components including

    (a) internal sources such as engines and plumes, and internal heat; and
    (b) external sources such as solar heating and background signature

All of these signature components must be considered in the analysis of a ship platform IR signature [20].

Measurement of IR signature consists of recording high quality IR images and the associated information. For each measurement, the following information is recorded [21]:

- IR Image: target, at least two reference blackbodies, spatial reference;
- Calibration: blackbody temperatures, distance to sensor, time of measurement, gain setting if used, spatial reference range and lens used;
- Target: range, gain setting, if used, and time of measurement;
- Sensor: lens used; sensor height with respect to ground; ground altitude with respect to sea level; and
- Weather: air temperature (°C) relative humidity (%), atmospheric pressure (mbar), visibility (km), instantaneous wind speed (m/s) and 24 hour average wind speed.

A camera is used to record the IR images of blackbody sources of emissivities and temperatures. The emitted radiance of a blackbody as seen by the camera can be calculated by integrating the Planck function:

$$L_{Sensor}(T_{BB}) = \int_{\lambda 1}^{\lambda 2} R(\lambda)\left[L(T_{BB},\lambda)\tau(\lambda) + L(T_{air},\lambda)(1-\tau(\lambda))\right]d(\lambda) \qquad (2.4)$$

$$L(T_{BB},\lambda) = \frac{C_1}{\pi\lambda^5(e^{C_2/\lambda T}-1)} \qquad (2.5)$$

where

$L(T_{BB},\lambda)$ is the radiance emitted by the blackbody at temperature T_{BB} (W/m²sr);
$L(T_{air},\lambda)$ is the radiance emitted by the blackbody in air (W/m²sr);
$R(\lambda)$ is the spectral response of the sensor used for measurements (values between 0 and 1);
$\tau(\lambda)$ is the atmospheric transmission along the path (values between 0 and 1);
$\lambda 1,\ \lambda 2$ are the spectral limits (wavelengths) of the sensor (μm);
$C_1 = 2\pi hc^2 = 3.7415\text{x}10^4$ Wμm⁴/cm²;
$C_2 = ch/k = 1.4388\text{x}10^4$ μm K;

h = Planck's constant = 6.626 x 10^{-34} Js;
c = speed of light = 299,792,458 m/s; and
k = Boltzman's constant = 5.670 x 10^{-8} $Wm^{-2}K^{-4}$

Equation (2.4) evaluates the radiance emitted by the black body at temperature T_{BB}, as altered by the atmospheric effects and has been utilized in the development of DRDC Valcartier's WinISAS IR signature analysis tool presented in section 2.5.2 below [21].

IR Suppression

Much like the case of radar signatures, stealth technology seeks to reduce IR signatures of ships in order to elude IR threat signature. IR suppression schemes can be organized into a four level system, including [20]:

(i)   No suppression (baseline platform)

(ii)   Basic cooling of visible exhaust duct metal, and skin cooling with available means

(iii)   Exhaust duct cooling, plume cooling to 250 °C, and skin cooling with available means; and

(iv)   Duct cooling, plume cooling to 150 °C, full skin cooling (with dedicated water wash for skin cooling for ships)
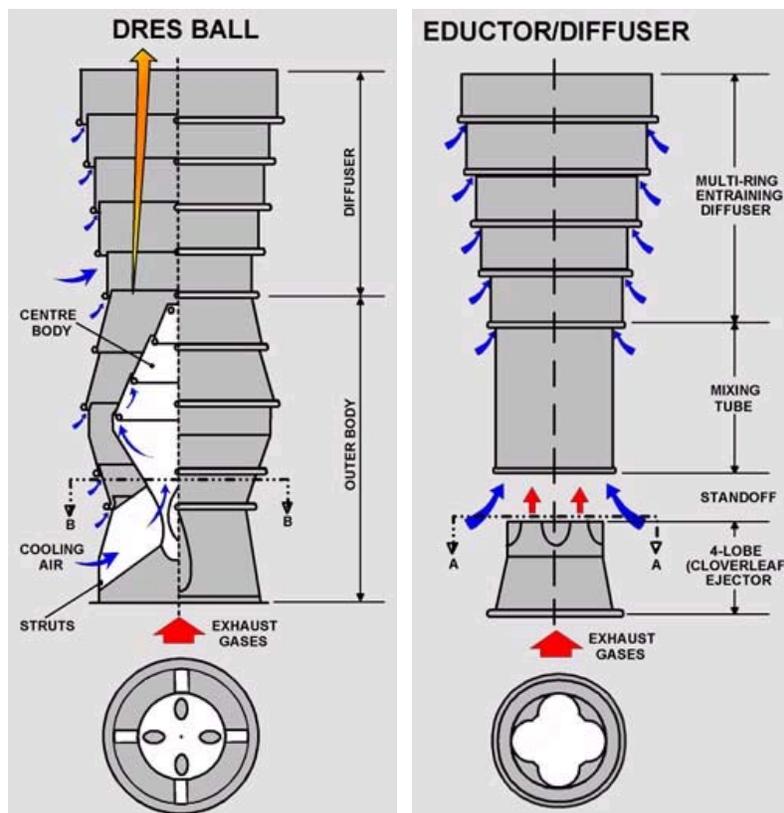
Figure 2.10: Eductor/Diffuser IR Suppression System [18,19]

Figure 2.10 shows the eductor/diffuser IR suppression scheme for ships. It consists of three main components: the ejector nozzle, the mixing tube, and the multi-ring entraining diffuser. The nozzle acts as an air-air ejector, pumping ambient air into the device. This ambient air mixes with the exhaust gases in the mixing tube, exiting at a much reduced average temperature. Finally, ambient air is naturally entrained in through the gaps of the diffuser, providing film cooling of the diffuser rings. The benefits of the eductor/diffuser include [20]:

- Scalable to fit any size uptake, both gas turbine and diesel.
- Similar plume and metal temperature reduction to the DRES-Ball.
- Offers protection to approximately 70° above the horizon.
- A 95% reduction in the vessel's infrared signature due to the gas turbine exhaust to the above angle.
- The simple design of the device makes it easily customized to any operating conditions or installation application.

The effectiveness of an IR suppression system is measured in terms of reduced IR susceptibility, which can be assessed using analysis tools. Toolsets available for modeling infrared signatures around ship structures are discussed below. It should be noted that the information provided here is based mainly on software vendor literature and publications available in the public domain. No independent evaluation of the software products was performed in this study.

2.5.2   Current Practices

ShipIR/NTCS

ShipIR/NTCS (Naval Threat Countermeasures Simulator) is an integrated simulation and modeling environment that computes the IR radiance of both ship targets and the maritime background, such as that shown in Figure 2.11 [23]. The model was developed by Davis Engineering and originally with support from DRDC Valcartier. The ShipIR component of the model has been adopted by both NATO and the US Navy as a common tool for predicting IR signatures. The US is now taking a lead role in further developing and validating ShipIR for use in the DD21 program. ShipIR/NTCS consists of several sub-models, including:

- An infrared sky radiance and propagation model (MODTRAN);
- A sea reflectance model;
- A surface geometry model which enables the modelling of complex ship geometries;
- A heat transfer model;
- A surface radiance model; and
- A plume emission model, which supports the prediction of both diesel and gas turbine plume radiance profiles.

Figure 2.11 Typical output from ShipIR (adapted from Ref. 22)

A block diagram illustrating the various sub-models of ShipIR is shown in Figure 2.12.
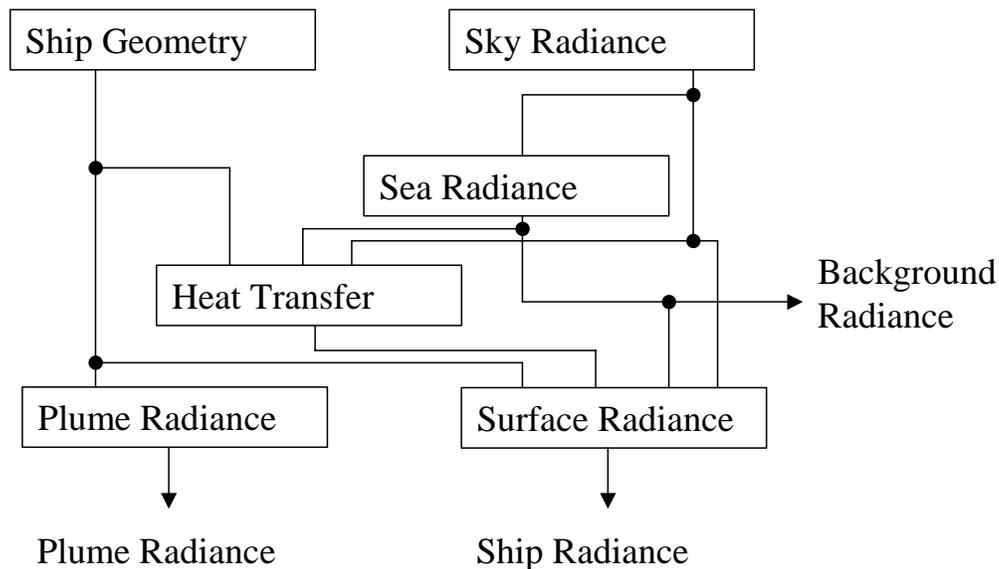
Figure 2.12: Block Diagram illustrating sub-models of ShipIR (adapted from Vaitekunas and Fraedrich, [23])

The model runs on an entry-level Silicon Graphics (SGI) workstation. The program relies on the colour image display for both signature analysis and to drive the engagement model. To achieve reasonable refresh rates and meet the necessary image resolution requirements, a unique set of display routines had to be devised to enhance the basic capabilities of the OpenGL graphics library. These routines, which include a multiple clipping plane algorithm, sub-image analysis, transparent plume-gas rendering, and automatic threshold detection, are described.

Types of analysis that can be performed by ShipIR/NTCS include the following:
  • Ship thermal analysis
  • Ship IR signature analysis

- Ship susceptibility to IR guided antiship missiles
- Ship design
- IR decoy countermeasures analysis; and
- IR suppression evaluation/benefits analysis

With various deployable countermeasures and missile/seeker heads modelled in NTCS, an assessment of ship survivability and the development of tactics and/or countermeasures necessary to provide adequate protection against IR threats can be studied. Current and future naval platforms can be analyzed for IR suppression effectiveness in such areas as hot surface visibility, low emissivity paints and engine exhaust signature suppression. A scenario is described using a Graphical User Interface (GUI), and simulated by updating pre-modelled components at discrete time steps. The results of the simulation are stored in summary and history text files which can be loaded into spreadsheet software for further data reduction.

Due to the large amount of processing required to produce a scenario, NTCS uses a 'snapshot' approach by accepting model data which has been pre-processed for one instant in time. At every time step during the simulation, a high resolution image of the particular scene is produced. The missile samples this image, processes it, and then the relative positions of all objects in the scene (targets and background) are updated without being reprocessed; hence, the term 'snapshot'. The simulation continues until a target has been hit or all targets have been passed by the missile. Vaitekunas and Fraedrich [23] have reported some validation studies carried out by the US Naval Research Laboratory (NRL) to assess the accuracy of ShipIR.

WinISAS

WinISAS (Windows Infrared Signature Analysis Software) is a computer program developed by DRDC Valcartier that is designed to perform calibrated analysis of IR images. WinISAS provides very precise calculation of the energy emitted by military sources as well as blackbody equivalent temperature. A WinISAS analysis requires as input, the image to be analyzed as well as information on the surrounding environment, temperature and spatial references. The analysis output for each target under study includes target's area in m^2, radiance in W/ m^2sr, absolute and contrast intensity in W/sr and the target's black body equivalent temperature (BET) in °C [21]. The primary steps in a WinISAS analysis involves the following steps:

- IR measurement: involving the recording of high quality IR images and associated information;
- Calculation of the spectral response of the IR camera;
- Radiometric calibration involving the calculation of blackbody emitted radiance as seen by the camera, according to equation (2.4);
- Spatial calibration aimed at establishing the field of view (FOV) of each pixel of image allowing for target area calculations; and
- Analysis calculations including the calculation of sensor radiance, black equivalent temperature (BET) of objects, source radiance; and contrasts;

ENSIR

Surface Optics Corporation (SOC), San Diego, CA has developed, ENSIR (ENSemble IR), a first-principles infrared signature analysis code that incorporates software modules for thermal analysis, atmospheric radiance calculations, signature prediction and radiance mapping. The radiance calculation is based on measured BRDF, HDR and directional emittance data of the

surface materials; no data fitting or parameterized models are required. This provides a fundamental calculation of the target signature. This data is generally produced from SOC instruments in a format that is directly read by ENSIR. The radiance module, DETECT, has been incorporated as part of the government standard Optical Signatures Code (OSC) and has been used for many years for producing signatures for strategic target discrimination studies. An important feature of IR signature analysis is the ability to accurately calculate surface temperatures of the target vehicle. ENSIR provides this ability in the TTRAN module. TTRAN is a fully time-dependent, three-dimensional thermal analysis code. Key features and highlights of the software are summarized below:

- ENSIR has been validated by many government and corporate agencies on many types of targets and backgrounds.
- ENSIR's unique design allows users to develop high fidelity, radiometrically correct IR signatures on multiple platforms (PCs or workstations).
- ENSIR's TTRAN module is a fully time-dependent, three-dimensional thermal analysis code, which uses lumped element nodal analysis technique. TTRAN supports multiple conductive, convective and radiative heat transfer paths, and produces transient and steady state temperature predictions with aerodynamic and terrestrial radiant environmental boundary conditions.
- It provides convenient interface to sensor models

MuSES

MuSES (Multi-Service Electro-optic Signature) is the next-generation infrared signature prediction program from ThermoAnalytics, Inc., Calumet, MI. MuSES provides complete thermal modeling and IR signature prediction within an integrated easy-to-use graphical interface. MuSES can be used to develop a comprehensive understanding of thermal signature drivers under realistic environmental conditions and locations. In addition to diffuse signature prediction, Multibounce BRDF rendering of band-specific radiance with atmospheric path attenuation gives true apparent temperature at the sensor [22].

2.5.3   Summary of Data Requirements

Geometric Properties

- 3-D configuration of ship geometry, including location and size of weapons, sensors, and other equipment;
- Propulsion and auxiliary engine exhaust properties for range of power settings;
- Ship insulation plan drawings;
- Internal machinery layout and exhaust routing arrangement drawings;
- Ship ventilation plan drawings (machinery room ventilation is most important);

Non-Geometric Properties

- Technical data (specifically thermal properties and geometry) on weapons, sensors, and other equipment;
- Ship surface properties, namely paint selections (spectral emissive data);
- Data on other miscellaneous sources of thermal IR, for example: galley stove exhausts, effluent discharges, heated widows;

Supplementary Data

- range of environmental conditions under which the ship is to operate.

2.6 Electric Potential Signature and Cathodic Protection

2.6.1 Technical Background

Metal structures will corrode in aggressive environments if they are left unprotected. Although surface coatings will inhibit the corrosion process, for long-term protection a cathodic protection system with sacrificial anodes or impressed anodes is generally used. These systems set up an electrostatic field in the electrolyte (e.g. seawater), which can protect the structure from corrosion if the correct level of the electrical potential is achieved. The designer's task is to determine the location and capacity of the anodes so that the whole structure is protected efficiently. However, the electrostatic field produced during the operation of active cathodic protection equipment also represents one of the non-acoustic signatures, which pose a mine threat to surface ships and submarines. Minimizing the underwater electric potential field is therefore an important consideration in assessing the cathodic protection system of naval platforms.

The tools and data requirements for determining the underwater electric fields and cathodic protection modeling are very similar and are thus included together in this section. The main difference between the two analyses is that the underwater electric potential model examines the potential distribution in the water surrounding the ship, whereas the cathodic protection modeling examines predicted potentials and current densities on the wetted surface of the ship. As the cathodic protection system is the prime source of the underwater electric field, the same model can be used for both purposes.

The corrosion process involves the flow of electrical current from one metal surface to another and is governed by LaPlace's equation for steady state conditions. Solving the equation, with the appropriate boundary conditions, yields the potential and current density on the structure and in the medium surrounding the structure.

2.6.2 Current Practices

Both boundary element and finite element computational methods have been used to model corrosion processes. However, use of the boundary element method is more widespread since only the boundary between the electrolyte and structures are modelled, reducing the computational effort required. Two examples of software that utilize the boundary element method for modeling of cathodic protection systems and underwater electric field are the commercial software package BEASY-CP, developed and marketed by Computational Mechanics Inc, and CPBEM, developed by Martec Limited for DRDC Atlantic.

2.6.3 Summary of Data Requirements

Model input parameters for both corrosion analysis and underwater electric potential include:

Geometric Data

A detailed description of the geometry of the wetted hull and any submerged appendages such as shafts, propellers and rudders. As the modeling technique deals with the surfaces of the structure, the equivalent surface area of any materials exposed directly to the seawater needs to be accurately represented by the model (typically this includes the propeller)

Material Data

Paint quality and paint damage of the wetted surfaces. Typically the degree of damage is represented as a percentage of exposed metal surface at a given location.

Potentiostatic polarization curves for any wetted surface material exposed to seawater (either by design or through paint damage), including sacrificial anodes. The polarization curve represents the relationship between current density and electric potential (relative to a standard electrode).

Cathodic Protection System

A description of the cathodic protection system. This includes: the location and number of impressed current anodes; location and number of reference electrodes; location, number and size of any sacrificial anodes; as well as a general description of the operation of the impressed current control (control algorithm, maximum anode currents, number of power sources, typical set points for reference electrodes, etc.).

Supplementary Data

Other factors considered in the models relate to the operating environment and include such things as:
- Conductivity of the surrounding seawater
- Littoral geometry
- Ship speed and propeller rpm
- Nearby marine structures (i.e. ships, piers, pipelines, etc.)

2.7   Magnetic Signature

2.7.1   Technical Background

Influence sea mines often have magnetic sensors to detect disturbances in the earth's magnetic field caused by the presence of a ship. These disturbances are the result of a combination of permanent and induced magnetic fields around a ship. To minimize the vulnerability of modern warships to such mines, ships magnetic signatures must be minimized. This can be achieved through the use of various signature reduction and control techniques including degaussing systems (DEGS). The DEGS neutralises the disturbance field with a counteracting field generated from an electric cable coil system connected to a DEGS coil current control. Such a system can be used to counter the magnetic signature resulting from both the induced and permanent magnetization of a ship. Up to 95% of a ship's disturbance can be neutralised with a DEGS.

A ship's total magnetic signature is a combination of a permanent magnetic field and an induced field. The permanent magnetic field is the field caused by magnetized materials on board the ship. When steel is stressed while in the presence of an external field it will become magnetized. Over time the permanent magnetic field surrounding a ship can become significant. Navies depend upon deperming stations to alter a ship's permanent magnetization. At such stations webs of cable are wrapped around a ship and then charged with electricity to create an electromagnet. In this way, a ship's permanent magnetic field is aligned with that of the earth's, thereby reducing a ship's magnetic influence on such mines and reducing the energy inputs for a degaussing system.

A ship's induced magnetic field is the result of the influence that magnetic materials (primarily steel) exert upon an external (earth's) magnetic field.

Finite element analysis programs that include magnetostatic analytical modules can be used to compute the magnetic disturbance caused by a ship. Since the region of interest, i.e. the region in which the magnetic field needs to be computed, is the volume surrounding the ship (for which relative permeability is 1.0) a scalar magnetic potential formulation is sufficient. Modelling of the ship, including any significant steel components and the degaussing coils, can be approximated within the confines of a scalar potential numerical computation, even though this involves some degree of approximation of the effect of the steel. Alternately, a mixed system in which the surrounding nonmagnetic volume and the degaussing coils are described by scalar potential models and the ship magnetic material is described by a vector potential model, can be utilized. This is a significantly more complicated model for which the application to ship magnetic signatures has yet to be explored.

2.7.2   Current Practice

Magnetic signature computation involves the use of FLUX-3D, a finite element based program for electromagnetic and thermal analyses. FLUX-3D has been developed and distributed by CEDRAT of Cedex, France. It is capable of performing magnetostatic, magnetodynamic and transient magnetic analyses. Of current interest is the magnetostatic analytical capability.

Current practice is to develop a complete finite element model of the ship structure, which for naval warships are typically made of steel, and then add significant non-structural steel ship components. MAESTRO is used to develop the structural model, which is incorporated into FLUX-3D. MAESTRO models use a variety of surface and line elements to describe a ship structure. The process of importing this data into FLUX-3D involves a number of steps and is somewhat labourious. The complete MAESTRO model can be unduly refined in some areas. In addition, any adjacent sections that are connected by multi-point-constraint equations need to be changed to ensure adjacent elements share common element edges. Otherwise, FLUX-3D would most likely have difficulty creating a volumetric mesh of the ship and its surroundings. Hence, the MAESTRO model is imported into a specialized version of Trident FEA, which includes a customized element merging capability. In Trident FEA elements are merged and element connections are reviewed. The resulting Trident FEA model will be made up of a limited number of element types including plates, beams, bars and stiffened plates. Importing the Trident FEA model into FLUX-3D requires conversion into DXF file format.

Since the ship structure makes up only a fraction of the total amount of steel in a ship, the additional non-structural steel components need to be added to the structural model. The most significant non-structural steel components tend to be machinery and other bulky components, which are not easily modelled by plate elements. Since FLUX-3D can import only 4-sided flat surfaces, the bulky non-structural components must be modelled within FLUX-3D.

The selection of magnetic material property values has been based on approximate values that are adjusted by using field results to calibrate numerical models.

2.7.3   Summary of Data Requirements

Geometric Data

The shape, size and (magnetic) material description of all major ship components made of ferrous materials, including structural and non-structural components are required.

Geometric descriptions of all structural steel should be available from the central database. This should provide a description of the geometry down to a resolution of 1 to 2 meters. Partial descriptions of some non-structural steel components, such as engines, generators, shafts, etc. should be available from the database. However, it is unlikely that such a database would be able to indicate the amount and distribution of ferrous material within such components. It is expected that this type of information would have to be extracted from an independent source. Likewise, magnetic material properties and descriptions of degaussing systems would probably have to come from independent sources.

Material Data

- induced and permanent magnetic properties of all ferrous materials

Magnetic Field Sources

- descriptions of major fixed magnetic fields (the earth's magnetic field),
- other major electrical circuitry that will produce large magnetic fields outside the ship (primarily the degaussing circuits).

2.8 Low Frequency Acoustic Signature

2.8.1 Technical Background

The techniques required for the determination of the acoustic pressures induced by a submerged vibrating structure are of considerable interest. The equations to be solved are of the same form as those required in wave scattering and diffraction, electromagnetic antenna theory, electrostatics, hydrodynamic oscillations of harbours, and wave forces on structures. Unfortunately, no closed-form solutions exist for arbitrary surfaces. Even for idealized shapes, where the motion needs to be prescribed, the number of analytical solutions in the literature is very small. In fact, for truly three-dimensional non-symmetric bodies there appears to be no published solutions.

Boundary integral formulations have long been recognized as an elegant and computationally economical method of modelling the compressible fluid loading upon a submerged elastic shell. The strength of an integral formulation of the acoustic problem is the reduction of dimensionality; the three-dimensional pressure field is represented by a two-dimensional integral relationship on the surface of the structure. The elegance of the method is the mathematical simplicity of the resulting integral expressions.

2.8.2 Current Practice

Under contract to DRDC Atlantic, Martec Ltd. has developed a series of computer programs, collectively named AVAST, for use in the numerical prediction of the acoustic radiation and scattering from floating or submerged elastic structures immersed in either infinite, half-space or finite depth fluid domains. AVAST combines both the finite element method for the structure and the boundary integral equation technique for the fluid. The finite element method is used to predict the natural frequencies and related mode shapes of the structure in-vacuo. The boundary integral equation method is used to define a relationship between the surface pressure and the normal surface velocities. The fluid-structure coupling is affected through matching the surface normal velocities.

2.8.3 Summary of Data Requirements

Geometric Data

The basic data requirement for boundary element based tools, such as AVAST, is a geometric description of the wet surface of the ship structure (including all appendages). In general, this geometric definition will be in the form of three or four-node facets or panels; however, some acoustic modeling tools (including AVAST) support higher order isoparametric panel formulations. The fidelity of the panel mesh is a function of the frequency at which the acoustic signature is to be computed (i.e.: the higher the frequency the finer the associated boundary element size). As a result, it is important that any tool(s) used to extract the structural geometry and generate low frequency acoustic models provide a capability for defining the appropriate mesh size based on frequency. It is anticipated that the number of

boundary elements required for the low frequency acoustic analysis (both radiated noise and target strength) of Canadian Forces vessels will exceed 15,000.

For cases where the elastic response of the ship structure is of interest, a global finite element model of the ship structure will also be required. This global finite element model is used to capture the global natural frequencies of the structure. In practice, researchers at both DRDC-Atlantic and Martec have used finite element models having a level of refinement similar to that found in Maestro [9] models, providing an upper frequency bound for ship structures (similar in size to the CPF) of approximately 30 Hz.

<u>Supplementary Data</u>

Additional information, in terms of hull coating impedances and the location of air-backed / water backed panels, will also be required for target strength prediction. It is anticipated that most, if not all, of this information will be stored as part of a SPM database. The only outstanding information, related to the material properties of the fluid domain, must be supplied by the user at run time.

2.9 High Frequency Acoustic Signature

2.9.1 Technical Background

For the past several years, Martec Limited, under contract from DRDC Atlantic, has been involved in the development of a new numerical technique known as Power Flow Finite Element Analysis (PFFEA) for evaluating high-frequency vibrational and acoustical characteristics of ship structures. This work forms part of Martec's collaboration with DRDC Atlantic in the Ship Noise Management Project, and it has motivated the development of the VASTF finite element program.

The basis of PFFEA is an analogy between the flow of high-frequency mechanical energy and heat conduction. This analogy results from applying the basic laws of energy conservation to an element of volume in a one- or two-dimensional structural component. The energy, which is carried from one part of the structure to another in the form of travelling waves, turns out to be governed by a second-order partial differential equation of the same form as a conductivity equation.   Furthermore, the mechanical energy flux (power flow) in a component is proportional to the gradient of the energy density, in a manner analogous to Fourier's law of heat conduction. The PFFEA method results from spatial discretization of the differential equations governing the energy distributions. Energy carried by each type of travelling wave (i.e.: flexural, torsional, etc.) is modelled separately in PFFEA, with coupling of the energies occurring at structural joints.

PFFEA is applicable to the analysis of random or broadband vibration, or narrowband vibration at frequencies where individual resonant modes are indistinct. Energy distributions predicted by PFFEA are time and locally spaced averaged, and as a result vary smoothly throughout a structural component. Relatively coarse finite element meshes can therefore be used in the modelling, making PFFEA much more efficient than conventional FEA approaches in the vibro-acoustic range. A further advantage of PFFEA is that the flow of energy in a structure can be mapped, enabling the visualization of transmission paths. This may be a valuable aid in the design of a structural system, and may also lend insight to an appropriate vibration control strategy.

PFFEA is similar to statistical energy analysis (SEA), in that the energy transferred between components is proportional to the difference in the energy densities of the components. The main difference is that in SEA, each component is modelled by a single response variable as opposed to the spatially varying response distributions predicted by PFFEA. It should be noted that because PFFEA is a finite element based method, PFFEA models can be generated directly from an existing finite element model, with only a small amount of additional information supplied by the user.

2.9.2 Current Practice

The PFFEA system developed at Martec over the past several years is now capable of analyzing relatively complex structural models. The system consists of three program modules: PFGEN, VASTF, and POSTPF. These are standalone modules that may be run separately, or together under the PFFEA driver program named SNAP.

2.9.3 Summary of Data Requirements

Geometric Data

One of the most demanding aspects of EFEA modeling is related to the development of a suitable mesh describing the geometry of the structure. Fortunately the EFEA approach has a significant advantage over other high frequency analysis methods in that it is compatible with finite element modeling, i.e., a finite element mesh of a ship structure could, in theory, be used as input to an EFEA analysis. In practice, the level of refinement used to discretize a structural model (i.e., number of nodes and elements) depends on what is of interest to the analyst, and as a result, the level of refinement could vary from location to location within the EFEA model. For example, it may be very important to model the spatial variation of energy within the engine room with a high degree of accuracy, but less important in the galley. As a result, the model of the engine room would be much more detailed

Although defining the overall geometry of the structure is an important issue, our experience has shown that what limits the size (i.e.: degree of refinement) of EFEA models is the level of effort needed to define the junctions (or connections) between structural components. SNAP uses a junction to define how energy is transferred between structural components at a structural discontinuity. At present, L- and T-connections are supported (unfortunately crosses are not). In the current version of the SNAP code, the definition of junction data must be prepared manually, and as a result, is extremely time consuming and error-prone. What is needed to make EFEA analysis practical for ship structures is a modeling tool that automatically computes the junction properties. Without such a tool, the complexity of models that may be analyzed using EFEA software is quite limited, perhaps to models containing fewer than 100 junctions.

Input Power Data

Another important issue related to EFEA modeling is the manner in which input power is defined. In the current version of the SNAP code, users define the input power in terms of forces and moments. The code then converts these loads into input power using the structural input impedance. The formula used in SNAP for computing the input power associated with a harmonic force of amplitude F_o is provided below in Equation (2.6):

$$P_{in} = Re\{F_o e^{jwt}\}Re\{v_o e^{jwt}\} \qquad (2.6)$$

Where v_o represents the velocity generated by the application of the force F_o. Working with time-averaged values, Equation (2.6) can be shown to be equivalent to Equations (2.7) and (2.8):

$$P_{in} = \tfrac{1}{2}|F_o|^2 Re\{1/Z\} \qquad (2.7)$$
$$P_{in} = \tfrac{1}{2}|v_o|^2 Re\{Z\} \qquad (2.8)$$

Where Z represents the input impedance. Expressions for the impedance are available in the literature, some of which have been coded in the current version of the SNAP code.

Given the fact that input power could be defined using either forces or velocities, it may be possible to convert source vibration data into applied power. Further investigation will be required in order to access the viability of doing so. Using vibration data measured by a

manufacturer may be difficult to apply directly because the input impedance used in the tests may not be known.

In summary, the SNAP software will allow for point load inputs applied to a select number of structural foundations (such as simple plates or beams). Using the structural information for that foundation, the input forces are converted to input power, which is the required input for the EFEA software. While the number of allowable input structures is presently limited, they are likely sufficient for a large number of naval applications and more complex types would be developed as required.

2.10 Flow Noise

2.10.1   Technical Background

Flow-induced noise arises from flow-induced vibrations. There are many classes of such vibrations including the familiar vortex-induced vibrations, galloping and flutter, and ocean wave-induced vibration of a riser. Of relevance to this project are those that potentially contribute to the radiated acoustic signature of surface ships. These are vibrations of ship structures that are exposed to external fluid flow (putting aside for the moment, on-board machinery noise). They include vortex shedding, fluctuating interaction loads, turbulent leading edge noise, turbulent boundary layer, and seaway-related loads.

In the flow past a bluff body, vortices are periodically shed. Their frequency and strength depends on the geometry and characteristic length of the bluff body and the ambient flow. They create a strong oscillating pressure field immediately downstream of the bluff body. Familiar examples include flow past structural ship members and submarine periscopes. An example of a fluctuating interaction load is that of an engine mount transmitting vibrations to the hull. These vibrations interact with the outside ambient flow past the hull at those points. Turbulent leading edge noise arises from the fluctuating pressure field that is created when an object is cutting through water. Leading edges of keels and the ship bow are examples. A turbulent boundary layer is created downstream of a body moving through a fluid. The fluctuating pressure field from the turbulent boundary layer will cause sound to radiate. An example is the boundary layer created on the plates of a ship hull as the ship moves through the water. The motion of a ship caused by the seaway (as characterized by the Response Amplitude Operators) will increase the flow-induced vibration radiated from a ship through several different mechanisms. The inflow conditions to the propeller will be constantly changing and likely increasing the propeller cavitation. These motions and their interaction with the sea create fluctuating pressure fields around the ship above and beyond those of a ship going through the water in a straight line.

2.10.2   Current Practices

2.10.2.1   TRANSOM

One of the primary goals of the Ship Noise Group at DRDC Atlantic is to reduce cavitation noise on Canadian Forces ships. Reduction in cavitation is achieved by improving propeller designs, which in turn requires an accurate prediction of the flow into the propeller. This flow is incompressible, has very high Reynolds number (approximately 10^9 based on ship length), can have complex geometry if propeller shafts, brackets, rudders, etc. are included, and has a free surface. Moreover, it is unlikely that the flow near the stern can be modelled adequately if wall functions are used. Consequently, solvers for this application have high memory requirements due to the large number of nodes needed. For several years now, DRDC Atlantic has been involved in the development of a multi-method solver, called TRANSOM, for this application [31].

TRANSOM (acronym for The Reynolds Averaged Navier Stokes Omnigenic Method) is a hydrodynamic computer program developed and maintained by DRDC Atlantic. It is intended

to solve a number of ship-related flow problems such as flows around submarines, vortex generated from propellers and control surfaces, and bilge vortex generation. The program provides a multi-block, multi-method Reynolds Averaged Navier Stokes (RANS) solver capability, such that the flow can be divided into several distinct blocks and different solution techniques can be applied to each block. TRANSOM solves the full Navier stokes equations in conjunction with a turbulence model and could hence solve flow around complex geometries of ships and submarines, with associated appendages. Two solution methods are available for use on each block: a pseudo-compressibility method that is suitable for structured blocks; and a finite element method that is suitable for unstructured blocks. Turbulence is modeled using a variant of the k-ε model or the Baldwin-Lomax model [32,33].

Validation studies have been carried out at DRDC Atlantic to compare the TRANSOM predictions with measured data or other numerical predictions. In one study, the flow past the SSPA 720 tanker ship was predicted with TRANSOM and compared with hot wire anemometry data. Figure 2.13 shows the profile of the tanker and Figure 2.14 illustrates the seven block TRANSOM grid used to model one half of the tanker and surrounding fluid [29]. The grid had a total of over 632,000 nodes. Spalart-Allmaras turbulence model was used, which required boundary conditions for pressure, velocity and Spalart-Allmaras viscosity [29]. General agreement between the TRANSOM calculations and the measured data was observed, and since the flow around the SSPA 720 tanker ship was expected to be similar to that around typical naval vessels, it was concluded that TRANSOM, with the Spalart-Allmaras turbulence model, could be used to adequately predict propeller inflow on most ships of interest to the Canadian forces.
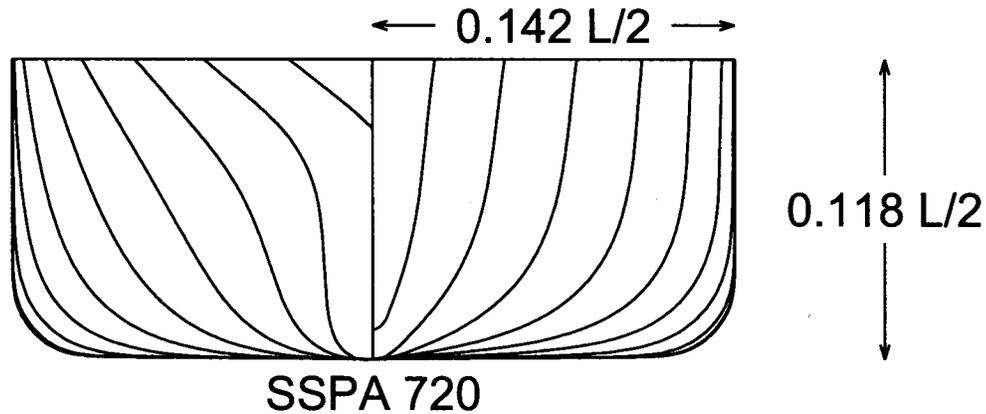

Figure 2.13: Offset diagram for SSPA 720 (L=ship length)
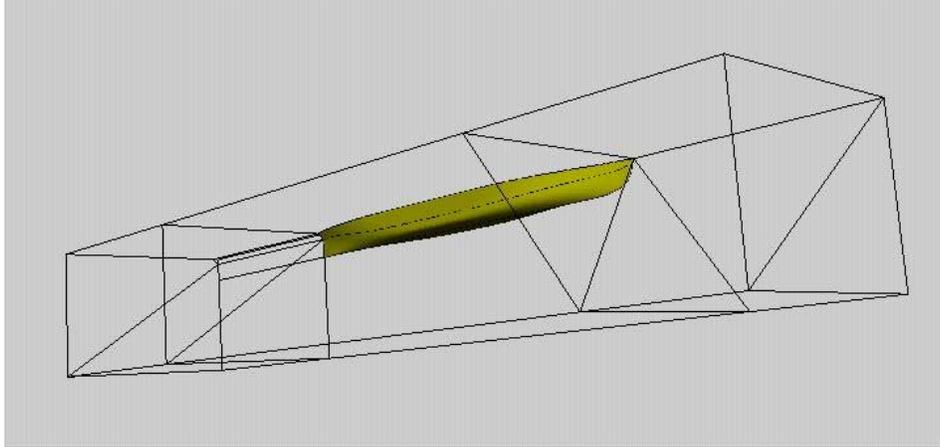
Figure 2.14 TRANSOM Grid Topology

2.10.2.2 ANSYS CFX

DRDC Atlantic also uses the commercial software ANSYS-CFX for predicting flow around ship structures. The CFX computational fluid dynamics product suite is now part of the ANSYS family of software. ANSYS CFX runs stand-alone, or integrated into the ANSYS Workbench engineering simulation environment, with the workbench providing a unified data sharing and project file management across the range of ANSYS products. ANSYS-CFX supports arbitrary mesh topologies, including tetrahedral, hexahedral, prism and/or pyramid elements, and used a hybrid finite element/finite volume approach to discretizing the Navier Stokes equations. The finite volume part enforces conservation over control volumes which are constructed around the mesh vertices or nodes, whereas the finite element part models variation with each element. [1]. An implicit second-order accurate time differencing scheme is used to model transient flows. A single solver is used to model both low-speed and high-speed flows, and both incompressible and compressible fluids can be modelled. ANSYS CFX can handle both laminar and turbulent flows. Several turbulence models, such as zero-equation turbulence, k-Є, RNG k-e, k-omega, Reynolds stress models, and detached eddy simulation (DES) turbulence model, are available. ANSYS vendor literature also suggests that a noise modeling capability is also available within the ANSYS suite for solving the acoustic wave equation, and that ANSYS permits the export of surface and rotating dipole sources information for acoustics solvers. It is also suggested that the ANSYS-CFX suite uses a multigrid solver technology that is scalable, meaning that the solution time per node is constant, no matter the mesh size, a feature that makes ANSYS-CFX attractive for solving large/complex problems.

DRDC Atlantic has performed studies to compare flow predictions by both the TRANSOM and CFX software. In one such study, by Hally and Watt [30], the authors used both programs to compute the evolution of laminar vortex. It was shown that both TRANSOM and ANSYS CFX (formally CFX TASCflow) generated accurate solutions. Hence it was concluded that both programs could be used to model vortex like flows with reasonable accuracy.

2.10.2.3 SNAP and Other On-Going Efforts

SNAP (acronym for structural noise analysis program) is a software tool developed jointly by Martec Limited and DRDC Atlantic for predicting high frequency noise [34], and has been discussed in the section on high frequency acoustic signatures. Martec, in collaboration with DRDC Atlantic and Noise Control Engineering, is currently undertaking a collaborative R&D effort to develop a flow noise modeling capability within the context of the energy finite element method. The fluid dynamic evolution cannot, of course, be modelled within EFEA to the fidelity expected of a dedicated computational fluid dynamics (CFD) analysis code. To incorporate these phenomena into EFEA one can model the phenomena as a distribution of oscillators defined *a priori*. The hydroacoustics of flow-driven and mechanically driven bodies can be regarded as a superposition of spatial distributions of monopole, dipole, and quadrupole oscillators. The SNAP code in its present form can model flow-induced vibrations that can be modelled as distributed point sources. The energy and intensity terms for the flow-induced vibration noise sources can be obtained from the power spectral density obtained through a superposition of localized flow monopoles, dipoles, and quadrupoles to capture the flow-induced noise phenomena.

According to Hally [28], efforts are also underway to provide flow noise modeling capabilities within the TRANSOM software tool.

2.10.3   Summary of Data Requirements

Geometric Properties
- 3-D configurations of wetted surfaces of hull, including appendages such as sonar dome, propeller shafts, brackets, rudders, etc

Flow Parameters
The parameters for defining the flow shall consist of
- Fluid density, viscosity
- Turbulence model variables;

2.11 Underwater Explosion

Naval ship structures must be designed specifically to withstand severe underwater explosion (UNDEX) loading caused by the detonation of weapons such as bombs, missiles, mines and torpedoes [35]. Such explosions will subject hull structures and equipment to initial impulsive shock loading and later-time pressure pulsations [36]. Specialized procedures for modelling the fluid dynamic interaction and loading, and resulting structural response and damage assessment, are required.

2.11.1   Technical Background

From a ship response standpoint, the two fundamental components of a underwater explosion are: (1) the short lived initial high pressure shock wave, Figure 2.15; and (3) the relatively long time low frequency bubble pulsation pressures, Figure 2.16.
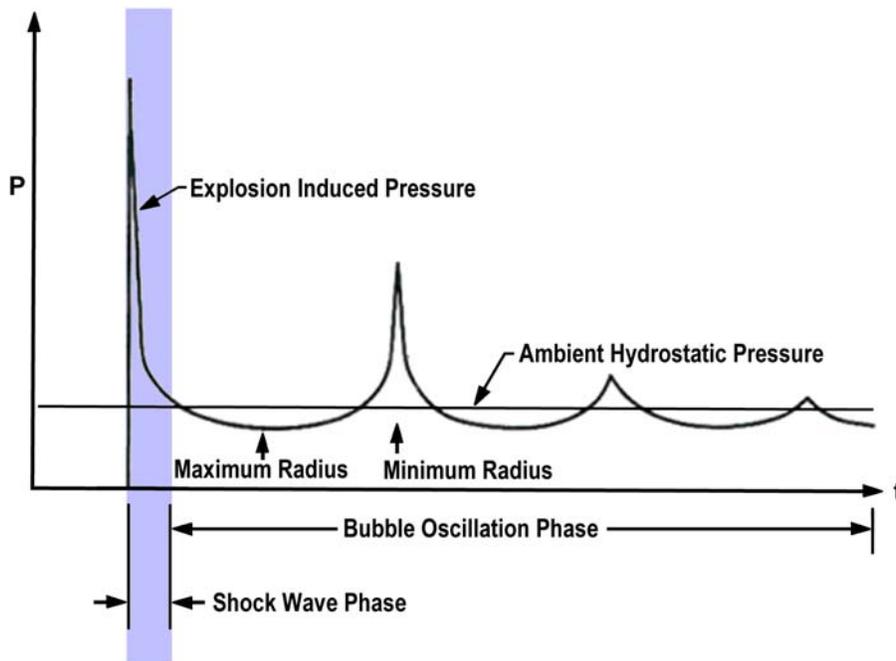

Figure 2.15: Shock Pressure Time History
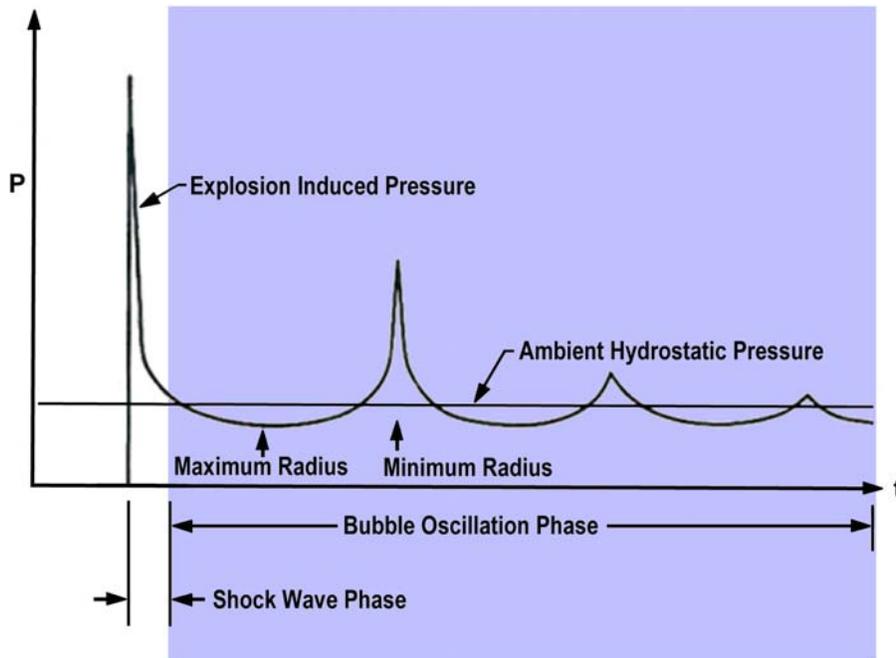
Figure 2.16: Bubble Pressure Time History

Two very different kinds of response are involved. One is local, in the sense that the response is confined to the region of the vessel closest to the explosion. The other is global, where the vessel as a whole responds to the explosion. Local response usually involves the excitation of high-frequency structural modes and is generally associated with the initial shock wave only. This shock can transmit motions into the structure and cause damage to mounted equipment. It can also cause damage to the structure itself. Global response involves the flexing motion (or whipping) of the whole hull in its low frequency vertical and transverse modes. This motion can be violent, and can cause damage in areas of the vessel far from the site of the explosion. Because of the proximity of bubble pulsation periods to the vertical and transverse vibration modes of ships, whipping is almost always associated with bubble/vessel interaction.

The mathematical modeling of the problem can be divided into two parts – one dealing with the elastic characteristics of the vessel (the structural part), and one dealing with the hydrodynamics (the fluid part).

For the structural part, the finite element method is generally used. Because of the two very distinct modes of response (i.e. global and local), it has been common practice in early years to use simple (equivalent beam) models for whipping analyses, and more complex 3D models for local high frequency shock analyses. Today, however, 3D models are also being used in global response analyses as well.

For the fluid part, three methods have emerged. These are: the Hicks method [37] for whipping analyses, the DAA (Doubly Asymptotic Approximation) [38], and CFD (Computational Fluid Dynamics) [39] for high frequency shock analyses. The Hicks method is used in conjunction with both the simple (equivalent beam) FE models and more complex,

but relatively coarse meshed 3D FE models. Strip theory is used to represent the effect of the surrounding water (i.e. added mass). Only ship-bubble interaction is considered, although the minor effect of the initial shockwave can be included. Both the DAA and CFD methods represent more general techniques, and are more adaptable to 3D finite models. The DAA method approaches exact solutions in the limits of zero and infinite frequencies in steady state problems, and, correspondingly, at long (e.g. bubble phase, low frequency) and short (e.g. shock wave phase, high frequency) time for transient response. Between these limits, a smooth (but reasonably accurate) transition is achieved. However, the DAA method can be used for far-field analyses only. The CFD method, on the other hand, can be used for near-field analyses.

Naval shock design standards have been developed over the years that allow shock analyses to be performed in a somewhat simpler manner. Using empirical formula and/or experimental results, procedures using base acceleration and response spectrum analyses methods have been formulated. Models can range from a one degree-of-freedom spring-mass system to a complex finite element model having many thousands of degrees of freedoms. The base acceleration analysis can be either static or dynamic. The response spectrum analysis, being based on modal methods, requires the calculation of natural frequency, modal masses and modal participation factors.

2.11.2   Current Practice and Toolsets

For the past 20 years, the Canadian DND have funded the development of a suite of computer codes for UNDEX analyses [40-42]. These UNDEX analysis codes allow for a wide variety of structural representations. These include:

- Full ships, as well as simplified structures like plates or cylinders,
- Beam, draft, area, inertia and weight versus length for simplified far-field shock analysis,
- Equivalent beam finite element models for simplified far-field bubble whipping analysis,
- 3-D finite element models for detailed far-field shock and bubble whipping analysis,
- Axisymmetric finite element models for near-field bubble analysis,
- 3-D finite element models for near-field bubble analysis,
- 3-D finite element models for near-field shock analysis.

The UNDEX analysis program consists of three basic components. They are: (i) UNDEX UndexShell Application Interface (API) [43]; (ii) the Trident finite element graphics system (Trident Graphics) software [44]; and (iii) the Trident finite element solver (Trident Solver) software [45].

The UNDEX analysis program provides links to the following additional components: (i) the USA (Underwater Shock Analysis) and companion CFA (Contained Fluid Analyzer) codes (Reference 6.4); and (ii) the Best Bubble code [46].

The Trident Graphics component provides the user with a general-purpose pre-and post-processor for finite element analysis, and with special features for UNDEX analysis. In addition, Trident Graphics:

- Provides links to finite element programs VAST, Nastran, ANSYS, SESAM and Dyna3D for model conversion and analysis.
- Provides links to graphics programs HyperMesh, Patran and HOOD for pre- and post-processing.
- Provides for link to wave-loading interface for determining draft, trim and heel, and generating equivalent beam models (cross-sectional properties and mass distribution) and hull form data.
- Provides link to VAST/USA/CFA.
- Provides link to VAST/CHINOOK.
- Provides capability to prescribe air or water backed plating.
- Provides capability to verify charge location graphically.
- Provides capability to verify CFD grid graphically.
- Provides capability for global/local (top-down) analysis.

The Trident Solver (VAST) component provides the user with a general-purpose finite element solver for the following UNDEX analysis requirements:

- Natural frequency analysis (dry and wet modes).
- Base motion analysis (static or time-history).
- Dynamic response analysis (shock and bubble pressure loading)
- Response spectrum analysis.
- Stiffness and mass matrices for USA code.

A recent development related to the UNDEX toolsets has been the incorporation of a capability to take into account the strain rate effect for elastic-plastic deformations and the implementation of various failure criteria for predicting structural failures in different modes.

2.11.3   Summary of Data Requirements

Geometric Data

- Full ship coarse mesh 3D FE model (including lattice/enclosed masts)
- Full ship coarse mesh wetted surface models
- Full ship equivalent beam model (may be derived from full ship 3D FE model)
- Detailed local 3D FE Models

Weight/Mass

- Structural (may be represented by material densities)
- Non-structural (X, Y and Z coordinates needed)
- Longitudinal distribution (may be derived from full ship 3D FE representation)
- Entrained fluid mass (may be automatically calculated)

Material Properties

- Young's modulus

- Poisson's ratio
- Density
- Yield stress (static and dynamic)
- Plastic stress-strain relations
- Cowper-Symonds D and p constants (strain rate effect)
- Rupture strain and dynamic ultimate shear strength (failure modes)

Fluid Properties

- Density
- Speed of sound

Charge Data (Reference 6.9)

- Weight, W (pounds or kilograms)
- Standoff, R (D, H, L) (feet or meters)
- Shock wave parameters, K1, K2, K3, K4, A1, A2, A3, A4
- Bubble pulse parameters, K5, K6

2.12 Above Water Blast Modeling

2.12.1 Technical Background

Steps in the design/analysis of a structure for blast involve computation of the blast load and then the mechanical response of the structure to the blast load. For ship structures, several considerations have to be made for these applications as discussed in the following subsections.

2.12.1.1 Blast Loads

First of all, the source and nature of the blast or explosion is an important consideration for accurate modeling of the blast load. Potential sources of blast include explosions from enemy weapons, gun backfire, accidental explosions from engine room, boiler room, or gas tanks, and underwater explosions. The nature of the blast loads from these sources can be categorized as follows:

1. High Explosives (HE): Conventional weapons and terrorist bombs are examples of high explosive threats. The energy released from HE is due to rapid chemical reaction or detonation of the explosive material.
2. Vapour Cloud Explosives (VCEs): VCEs may result from an accidental release of cargo that forms a flammable cloud and explodes. Depending on the strength of the ignition source and proximity of obstacles that might increase the turbulent burning of the cloud, a vapour cloud explosion might proceed as a deflagration (with subsonic burning) or a detonation (with supersonic burning).
3. Dust Explosions: Fine dust in suspension may burn rapidly enough to produce blast pressures, depending on the materials involved and the venting available.
4. Bursting Pressure Vessels: Should a pressurized gas cylinder (or similar vessel) rupture, a blast wave will be created. Unlike the first three examples, which are driven by a chemical reaction, blast waves from a vessel burst are created by a physical explosion.
5. Boiling Liquid Expanding Vapour Explosions (BLEVEs): The energy from a BLEVE is from a sudden change of phase of stored material. Tanks of liquids immersed in pool fires BLEVE when the contents increase in temperature and vapour pressure exceeds the capacity of the tank (which decreases in strength with the increasing temperature). The burst is accompanied by a sudden flashing of a portion of the contents from liquid to gas, which rapidly expands to create a blast wave.

All of these explosion sources produce a sudden release of energy that generates a blast wave and a rapid pressure rise that expands outward into air and decays in strength with distance from the source [65]. The blast wave causes rapid variations in pressure, temperature, density, and particle velocity as it travels through the air. Figure 2.17 shows how the pressure from a blast wave changes with time. This example is for a shock wave, which, traveling supersonically produces an instantaneous pressure increase that then decays with time. The ambient pressure, P_A, rises abruptly with the arrival of the shock front at time t_a. In an ideal shock wave this is a discontinuous pressure jump to a peak value P_0^+. The pressure decays to ambient in a time, t_0^+, then drops to a partial vacuum of amplitude P_0^- before returning to ambient pressure after a duration t_0^-. The integral of the pressure-time curve (graphically the area under the curve) is the specific impulse, a key parameter in blast assessment.
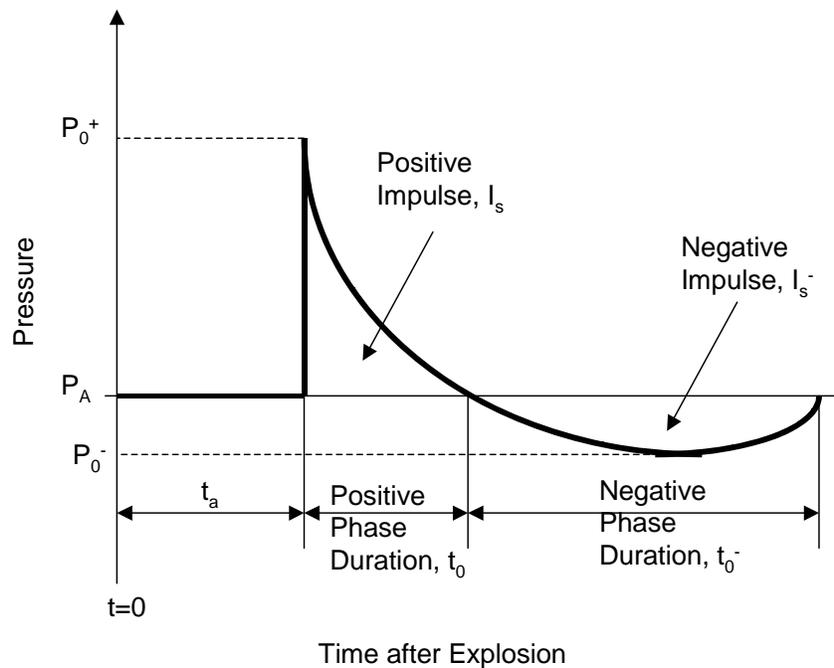
Figure 2.17: Pressure-Time History for an Ideal Blast Wave

The portion of the pressure history greater than ambient pressure is called the positive phase, and that below ambient is called the negative phase. Since the strongest positive phase loads generally govern, the positive phase peak pressure and the impulse are the two key characteristics of the blast wave needed in assessing dynamic structural response.

For naval vessels, HEs are considered the most significant sources for blast threat. The most important parameter characterizing a HE source is its total heat of detonation, E, which is proportional to the charge weight. Blast loads are predicted for high explosive blasts using Hopkinson-Cranz scaling, which relates blast parameters to the charge weight rather than energy. The scaled distance Z is given by

$$Z = R / W^{1/3}$$

where W is the total weight of a standard explosive such as TNT, and R is the stand-off distance between the charge and the structure. The scaled impulse $\bar{I}$ is defined as

$$\bar{I} = \frac{I U_s}{W^{1/3} P_A^{2/3}}$$

where I is the impulse, U_s is the speed of sound in air, and P_A is the ambient pressure. R is the standoff distance between the charge and the structure.

Airblast curves have been developed for spherical TNT charges by several investigators [50, 55, 68]. Figures 2.18 and 2.19 show typical free-air blast curves for estimating overpressure and dynamic pressure, and their corresponding durations.
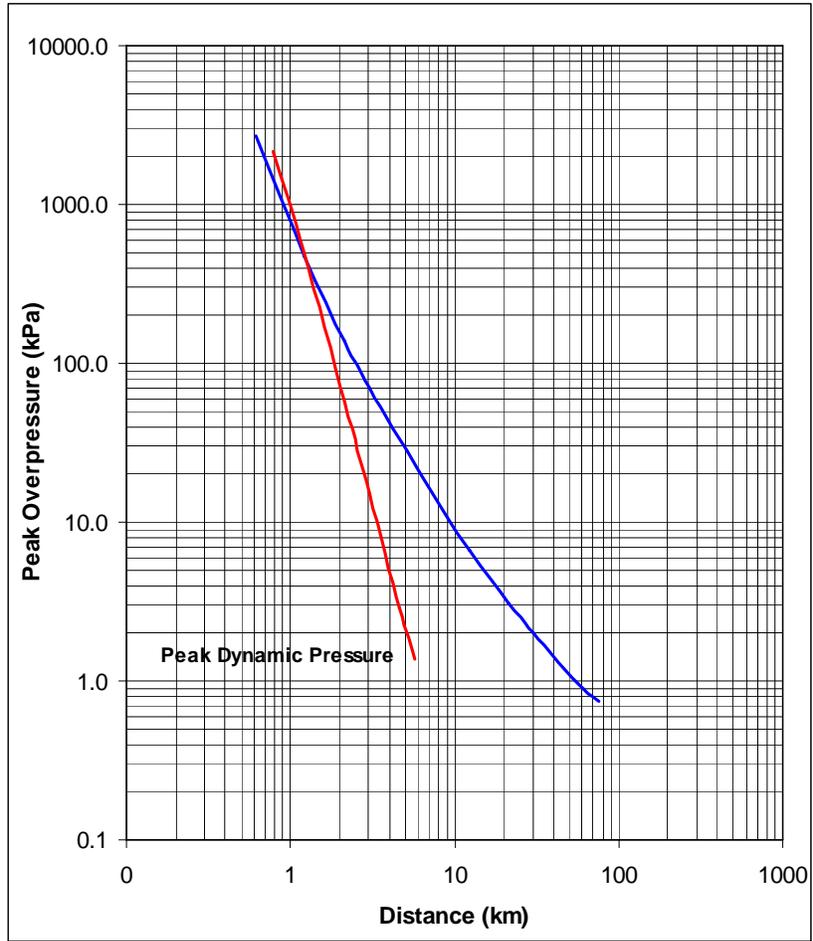
Figure 2.18: Overpressure Versus Standoff Distance for 1-MT Weapon (adapted from Ref 50)
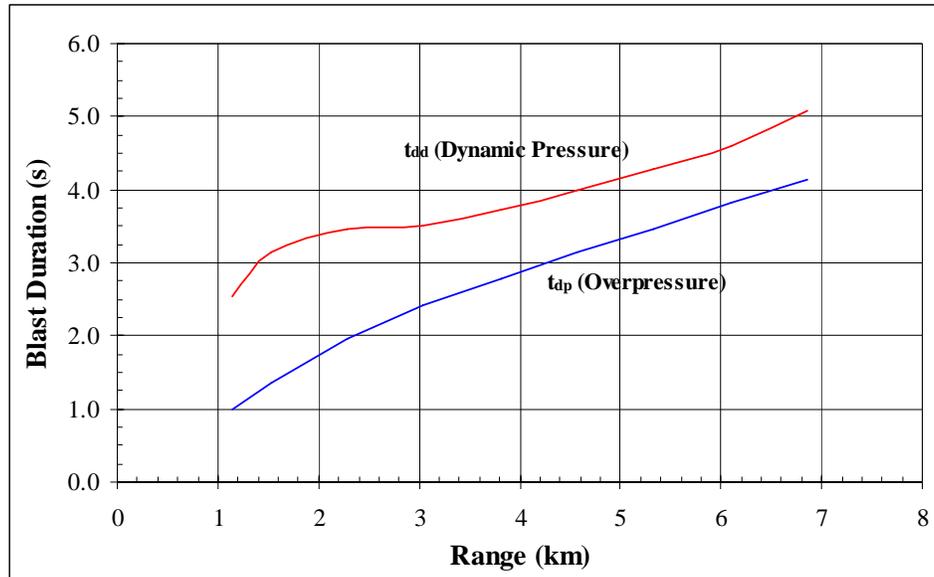
Figure 2.19: Overpressure and Dynamic Pressure Positive Durations Versus Range (1 MT Weapon) [50]

These curves are based on explosive charge weights of TNT. While the detonation energy varies with the specific explosive used, a TNT equivalence may be determined by equating the detonation energy per unit mass to that of TNT. Table 2.2 presents the energy and TNT equivalence for a number of explosives.

Table 2.2: TNT Equivalence of Various Explosives

Explosive	Detonation Energy (kJ/kg)	TNT Equivalence
Amatol	2650	0.586
Baronal	4750	1.051
Comp B	5190	1.148
RDX	5360	1.185
Explosive D	3350	0.740
HMX	5640	1.256
Lead Azide	1540	0.340
Nitroglycerin	6700	1.481
Pentolite 50/50	5110	1.129
TNT	4520	1.000
C-4	4870	1.078
Blasting Gelatin	4520	1.000
ANFO	3750	0.830

The tools for computing the blast loads must be capable of modeling the various types of blasts. Another important consideration in the computation of the blast load is the location of

the blast as well as the configuration of the structure being subjected to the blast. Consider for example the typical ship structural components shown in Figures 2.20 and 2.21. For an external air blast the blast loading on the deck, hull or superstructure structure could be estimated from the commonly used approaches. In these approaches the load is generally governed by the maximum overpressure, shape of the pressure history and duration; or the speed and acceleration of the blast wind [47], as discussed above. For an internal blast the situation is greatly complicated by the presence of stiffeners, girders, bulkheads, doorways and other openings, etc and the use of these methods could lead to grave errors in the blast load estimates. The computer programs such as SHOCK [63] and FRANG [62], developed by the Naval Civil Engineering Laboratory, can be used for assessing the shock and quasi-static loads for confined explosions. Alternatively, computational fluid dynamics codes, such as CHINOOK [51] can provide a more exacting and appropriate approach for an explosion inside a more complex structure.

Conventional Single Hull Structure   Advanced Double Hull Structure
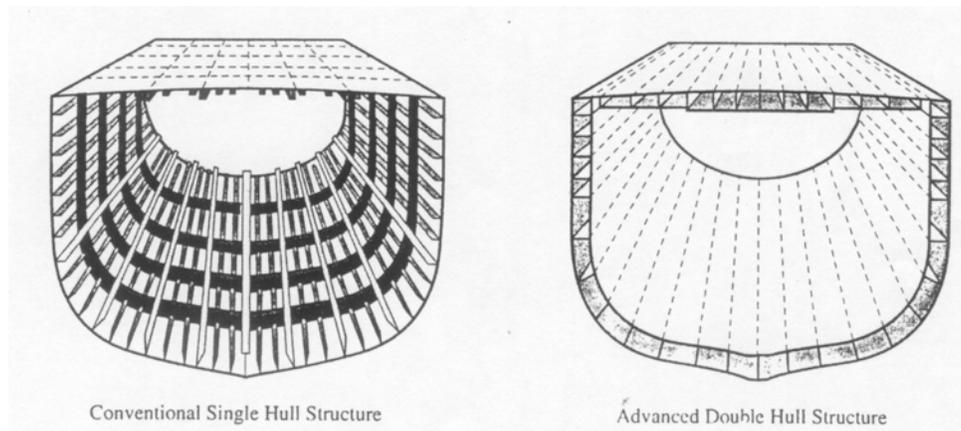
Figure 2.20 Typical Ship Structural Components for Single and Double Hull

Structures (Melton et al, [61])
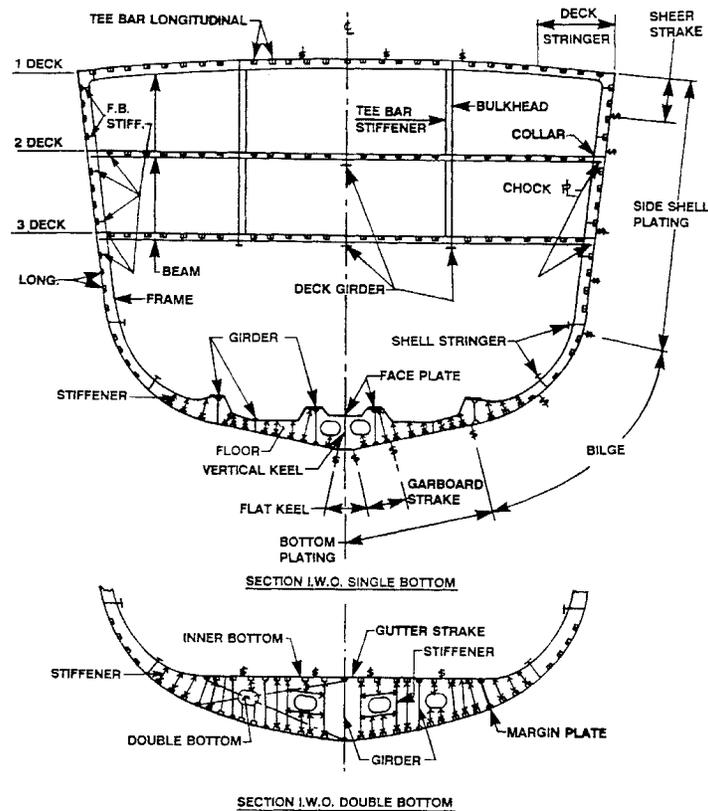
Figure 2.21. Typical Ship Structural Section for single bottom and double bottom hulls (Structural Practices Standard [67])

2.12.1.2 Structural Response to Blast Loads

Simplified Versus High Fidelity Methods

In computing the response of the structure due to blast load, the following methods have traditionally been used in ship structural applications:

Simplified analyses using SDOF models in which the response to the blast pressure history is obtained by numerical integration of the dynamic equations of equilibrium for a single response mode. The response is obtained in the form of maximum response and time to maximum response or in the form of iso-damage (or P-I) curves [47; 49]. These models have limited use because of the assumptions inherent in them. However, they can prove to be useful for preliminary design situations.

- Rigid plastic methods for dynamically loaded rectangular beams and plates with large deflection effects have been developed by Jones [54], and have been applied for ship structural panels. Schuback, et. al. [66] have recently extended the method to model

one-way and two-way stiffened grillage structures. The method has further been extended to provide iso-damage curves for grillage structures. These methods are simple and easy to use and can provide meaningful results for navy grillage structures, especially those with flat geometric configurations.

- Finite element based methods are based on the fundamental descriptions of the physical process. They are the most versatile (can handle complicated geometries, loading and boundary conditions) and can model the full nonlinear-elastic plastic behavior of the blast-loaded structure. Commercial finite element software with these capabilities abound but accuracy is a concern. Several attempts have been made to calibrate some of the finite element codes for blast analysis. In this regard, reasonable accuracy has been recorded with codes such as DYNA3D, ABAQUS, ADINA and Trident FEA. The advent of faster computers now makes it possible to obtain simulations of fairly complex structures on personal computers. However, the sophistication and complexity of using these methods poses some limitations. Studies on the development of simplified finite element methodologies geared specifically to stiffened plate structural components of ship structures have been undertaken [56; 57]. The method has recently been extended to box structures and to stiffened composite structures. These methods are currently being used by DRDC Suffield in their air blast-modeling program [52] where calibration studies are also being undertaken. These full blown or simplified finite element approaches can be effectively used to model the response of the structures to blast loads.

Acceptance Criteria

Design for conventional loads according to working stress design (WSD) philosophy is based on limiting stress levels to acceptable levels that ensure structural components do not deform plastically. For blast resistant design, most structural components are designed to deform plastically, but not to fail. Hence, acceptance criteria are based on deflection or strain limits rather than stress limits. The level of response that is deemed acceptable is a function of the type of material, the response mode, amount of ductility, level of protection that is desired for personnel and equipment, and the confidence in the design and analysis approach (both the loads and structural analysis).

The "Interim Guidance Notes for the Design and protection of Topside Structures Against Explosion and Fire" [53] states that deformation limits can be set as a proportion of the span, as an absolute deformation, as a member shrinkage limit, or as a ductility ratio based on strain limits. A limit set as a proportion of the span is similar to the support rotation limit for buildings, set by the American Society of Civil Engineers (ASCE). An absolute limit may be required if personnel or critical equipment is located close to the deforming structural component. A member shrinkage limit may be required to ensure that the ends of a component do not undergo unacceptable axial deformations. Ductility ratio limits are based on the capacity of the material to deform plastically. Table 2.3 provides strain limits suggested by the Interim Guidance [53] and API Recommended Practice 2A-WSD [48] for offshore structures.

Table 2.3: Suggested Strain Limits

Type of Loading	Type of Section	Strain Limit	
		Interim Guidance	API 2A-WSD
Tension Member		5%	5%
Member in Bending or Compression	Plastic Section	5%	5%
	Compact Section	3%	3%
	Semi-Compact Section		1%
	Other Sections	1%	< Yield Strain

The Lloyd's Rules and Regulations for the Classification of Naval Ships [60] does not specify quantitative response limits for ship structural components subjected to blast loads. Rather, a qualitative description of the response is provided, which is related to the complexity of the analysis performed, as described below:

- EB1 (External Blast) Assessment – A simplified analysis using simple design equations, which assumes elastic perfectly plastic behaviour with only small displacements.
- EB2 Assessment – An extension of the EB1 assessment. Displacement is limited to ensure that the structural response does not compromise the structural integrity, water or gas-tight integrity or functioning of critical items or equipment.
- EB3 Assessment – Failure criterion should be based on elastic-plastic methods considering local response of plating with large displacements and local bending response of stiffened panels. A lumped model can be used to evaluate the overall side sway of the ship structure. The response limits are the same as an EB2 assessment.
- EB4 Assessment – Employs a full non-linear analysis using finite element methods. Response limits must assure that primary hull girder integrity; water and gas tight integrity and functioning of critical components are maintained.

Material Properties

Under dynamic conditions, material behaviour can be significantly different than under static conditions. This is due to the strain rate and strain hardening effects as shown in Figure 2.22. A typical marine steel such as 350WT, has a well defined yield point followed by a plateau region where yielding takes place with little or no increase in load. As the material continues to yield, strain hardening takes place, requiring a stress increase for deformation to continue. At some point, the ultimate stress level is reached, and the material will then continue to deform with decreased load until the material ruptures.

Note that in the figure, the static stress-strain curve was obtained from actual measurements. However, for illustration purposes, a dynamic stress-strain curve has been added (but not measured experimentally) to show that both the yield stress and ultimate stress increase at higher strain rates. This occurs because the material cannot respond at the same rate as the load application.
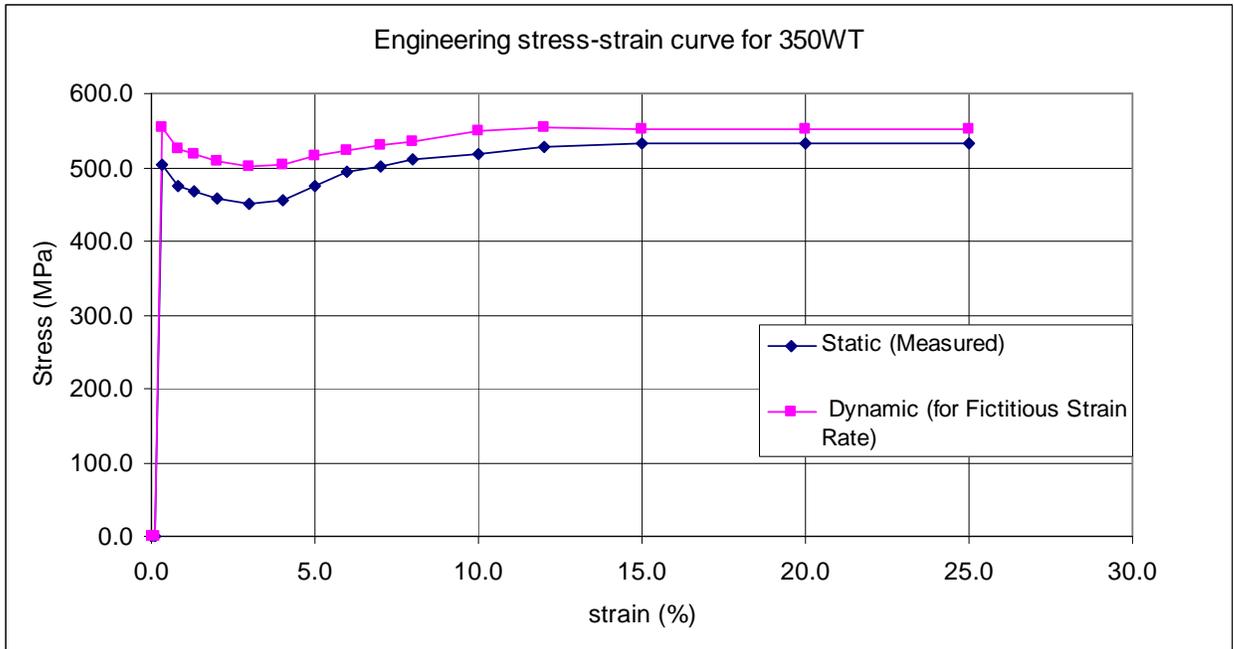
Figure 2.22. Typical Stress-Strain Curve for Steel (adapted from Ref 59)

The dynamic yield strength, f_{dy}, and the dynamic ultimate stress f_{du} are given by

$$f_{dy} = DIF_y f_y$$

$$f_{du} = DIF_u f_u$$

where

f_{dy}	=	dynamic yield stress
DIF_y	=	dynamic increase factor for yield stress
f_y	=	static yield stress
f_{du}	=	dynamic yield stress
DIF_u	=	dynamic increase factor for ultimate stress
F_u	=	static ultimate stress

Note that the modulus of elasticity, E, is not affected by the strain rate. Typical dynamic increase factors for several types of steel are provided in Table 2.4.

Table 2.4: Dynamic Increase Factors for Metals [68]

Material	DIF		
	Bending/Shear	Tension/Compression	Ultimate Stress
A36	1.29	1.19	1.10
A588	1.19	1.12	1.05
A514	1.09	1.05	1.00
A466	1.10	1.10	1.00
Stainless Steel 304	1.18	1.15	1.00
Aluminum, 6061-T6	1.02	1.00	1.00

2.12.2   Toolsets

A number of blast and blast effects analysis software are available worldwide. Some of these are available commercially while others are available only to government organizations or are proprietary to the developers.   Table 2.5 shows a representative list of programs for performing blast and blast effects analysis.

Table 2.5: Selected Computer Programs for Blast Effects and Structural Response Modeling

Program Name	Type of Analysis	Method	Developer
BLASTX	Blast Prediction	Semi-empirical	Science Applications International Corporation (SAIC), USA
CTH	Blast Prediction	First Principle	Sandia National Laboratories (SNL), USA
FEFLO	Blast Prediction	First Principle	SAIC, USA
FOIL	Blast Prediction	First Principle	Applied Research Associates (ARA), USA
HULL	Blast Prediction	First Principle	Orlando Technology, Inc., USA
PAM-FLOW	Blast Prediction	First Principle	PAM System International, France
SHARC	Blast Prediction	First Principle	ARA, USA
CHINOOK	Blast Prediction	First Principle	Martec Limited, Canada
BLASTCAD	Structural Response	Semi-Empirical	Southwest Research Institute (SWRI) & SAIC, USA
DYNA3D	Structural Response	First Principle	Lawrence Livermore National Laboratory, USA
ESPA-II	Structural Response	First Principle	Weidlinger Associates, USA
FLEX	Structural Response	First Principle	Weidlinger Associates, USA
PAMSHOCK	Structural Response	First Principle	PAM System International, France
TridentFEA	Structural Response	First Principle	Martec Limited, Canada
ALEGRA	Coupled Analysis	First Principle	SNL, USA
ALE3D	Coupled Analysis	First Principle	Lawrence Livermore National Laboratory, USA
AUTOReaGas	Coupled Analysis	First Principle	Century Dynamics, USA & TNO, Netherlands
DYNA3D/ FEFLO	Coupled Analysis	First Principle	Lawrence Livermore National Laboratory & SAIC, USA
FUSE	Coupled Analysis	First Principle	Weidlinger Associates
MAZe	Coupled Analysis	First Principle	TRT Corporation
PAMSHOCK/ PAMFLOW	Coupled Analysis	First Principle	PAM System International, France
BlastFX	Blast and Structures	Semi Empirical	Northrop Grumman
MASTSAS	Blast and Structures	Semi Empirical	Martec Limited/DRDC Atlantic
Mast Tool	Blast and Structures	Semi Empirical	Martec Limited/DRDC Atlantic

The programs are categorized according to the type of analysis – blast prediction, structural response prediction, coupled fluid-structure analysis or blast and structures analysis. Also

shown in the table are the methods (semi-empirical or first principles) and names of the developers. Tools that are available in-house at Martec and DRDC Atlantic include CHINOOK [51], TRIDENT-FEA [69], MASTSAS [58], and Mast Tool. These tools can be adapted for the HF-SPM system.

2.12.3   Summary of Data Requirements

<u>Geometric Properties</u>
- Ship hull configuration above water, including detailed scantling information
- Super structure configuration, including detailed scantling information
- Mast structure configuration, including list of equipment, their dimensions and weights
- Configuration of all tanks and compartments, including detailed scantling information

<u>Blast Load Parameters</u>
  The parameters for defining the air blast loads shall consist of
- Peak overpressure;
- Duration of the over pressure positive phase;
- Stand-off distance;
- Blast location (aft, starboard, quarter starboard, etc.);
- Friedlander decay constant;
- Temperature and pressure
- Drag coefficient for various components; and
- Air density.

<u>Material Properties</u>
- Young's modulus
- Poisson's ratio
- Density
- Yield stress (static and dynamic)
- Ultimate stress (static and dynamic)
- Plastic stress-plastic strain relations, with strain rate effects
- Dynamic increase factors for yield and ultimate stress

<u>Acceptance Criteria</u>
- Plastic strain limit
- Permanent deformation limits for various structural components
- Displacement-span limit for various structural components
- Shrinkage limits for various structural components

2.13 Ship Structural Inspection Database (SID)

According to a DRDC website, "the Canadian Navy has initiated improvements to its maintenance practices for naval vessels through a program entitled the Naval Ship Maintenance Program (NSMP). The NSMP encompasses new survey and repair procedures and guidelines, a computer database to track inspection and repair actions (Structural Inspection Database - SID), and a process for certifying the structural integrity of each vessel (Ship Structural Integrity Program - SSIP)."

Structural **I**nspection **D**atabase Version 4 is a Windows based multi-user database system for recording, planning and controlling ship structural inspections and remedial action performed as part of routine ship maintenance. It was developed by MIL Systems.

The system facilitates control of all parts of an organization involved in ship structural maintenance. Inspection findings are stored systematically and consistently. Results can be viewed across the ship class allowing class problems to be promptly identified so that they can be addressed in a timely manner. The stored information can also be manipulated to perform degradation trend analyses permitting maintenance and inspections to be scheduled more rationally and cost effectively.

SID 4 consists of: SID Manager, Ship Model Builder, SID Query, SID Analyzer and SID Planner

While the data at the heart of each database is the history of structural surveys, defects and repairs, it is the ability of the SID program to organize this information by relating the data to the ship geometry/structure that makes the program so useful. This organization makes it possible to review and visualize the information by location or structural component.

The application of the defects to the detailed structural models for analysis will be implemented.

2.13.1   Technical Background

Martec has experience using information from the Ship Structural Inspection Database (SID). Martec created a hull surveyor guidance. The information was collated so that known class defects were split up into fatigue crack, corrosion and deformation defects. A graphical display of the information was then created for the Halifax Class frigates. The graphical displays were presented on the ship's general arrangement drawings, organized by deck. The data was created in a way so that information could be added, deleted or edited over the web securely.

2.13.2   Review of Current Practices

The Ship Structural Inspection Database (SID) is an application for recording, tracking, managing and analyzing data for structural surveys, defects and repairs. The system facilitates control of all parts of an organization involved in ship structural maintenance.

Inspection findings are stored systematically and consistently. Results can be viewed across the ship class allowing class problems to be promptly identified so that they can be addressed in a timely manner. The stored information can also be manipulated to perform degradation trend analyses permitting maintenance and inspections to be scheduled more rationally and cost effectively.

SID allows your organization to:

- Plan structural surveys.
- Record defects and affected ship components consistently.
- Track inspections and repair work.
- Control approvals of inspections and defects.
- Generate standardized reports.
- Search and report with user defined queries.
- Predict corrosion trends.
- Analyze defect data.
- Obtain feedback on design issues.
- Reduce inspection and repair costs.

2.13.3   Summary of Data Requirements

The defects that are to be applied to a FEM are fatigue crack, corrosion and deformation defects. Modification of a FEM would be an automatic procedure using information in the SID to adjust the model.

The definition of the defect in the SID must be in a consistent format so that the software can access the information properly. The definition of the defect must be accurate and comprehensive so that the detailed FEM can be accurately modified. The structural FEM must be large enough to contain the defect and produce accurate results.

3. Prototype Data Framework

An LCM prototype data framework, which illustrates the usefulness of the SPM concept, was created. It demonstrates some of the functional requirements that will be needed to develop the full LCM system required by the DND. As such, it illustrates the process whereby structural data can be extracted from an SPM database, processed, and supplied to a candidate analysis package – in this case Trident FEA for structural FEA.

3.1 Ship Model

In this prototype development, ShipConstructor was chosen as the SPM modeling tool. The ShipConstructor platform allows users to model ship structural data in the AutoCAD environment, and saves the data in its own management schema, which is stored in a Microsoft SQL Server database. A typical ShipConstructor structural member, referred to as a plate part, is shown in Figure 3.1.
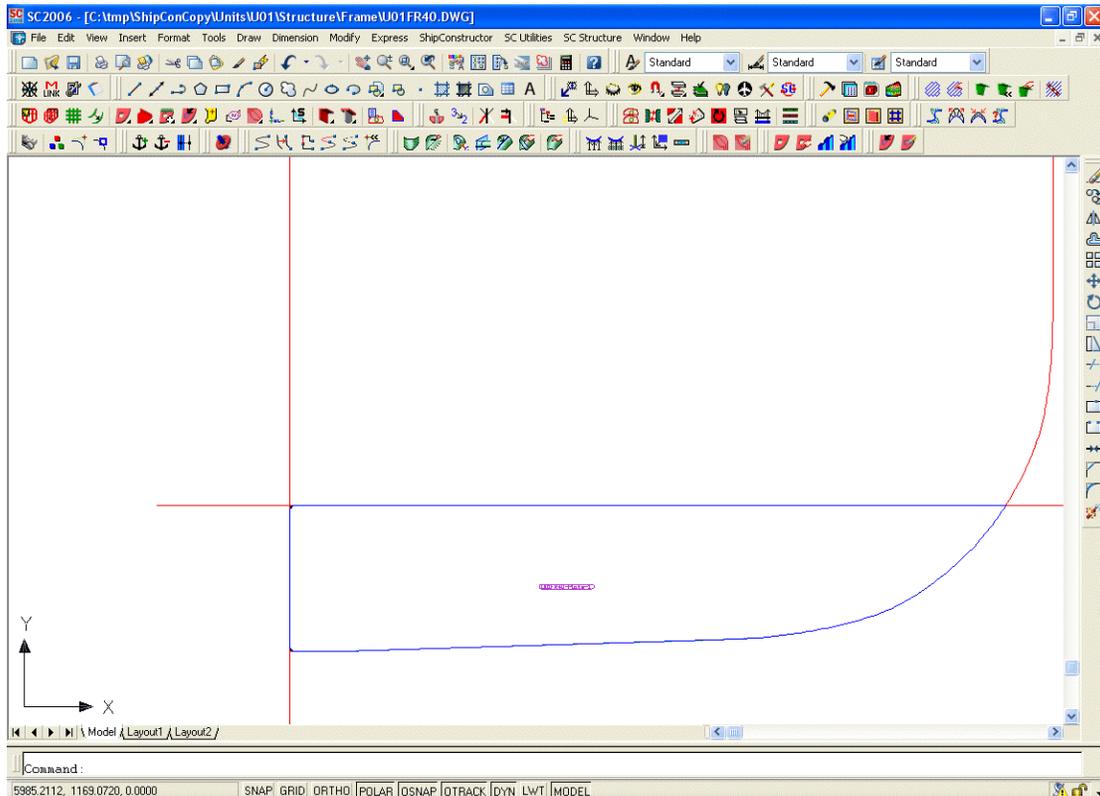
Figure 3.1 Bulkhead Plate Part in ShipConstructor

The ship structural model within ShipConstructor is categorized according to shipbuilding conventions – namely, the ship is divided into different units, each unit has panels, each panel has plates and stiffeners, and each stiffener or plate has cutouts, end cuts, etc. All of these entities are captured in the database schema, which also introduces the notion of an assembly

as a collection of these entities. Assemblies are arranged hierarchically to form an overall model. Figure 3.2. illustrates some of the tables comprising the ShipConstructor database schema, as accessed through the ShipConstructor Database Manager tool.
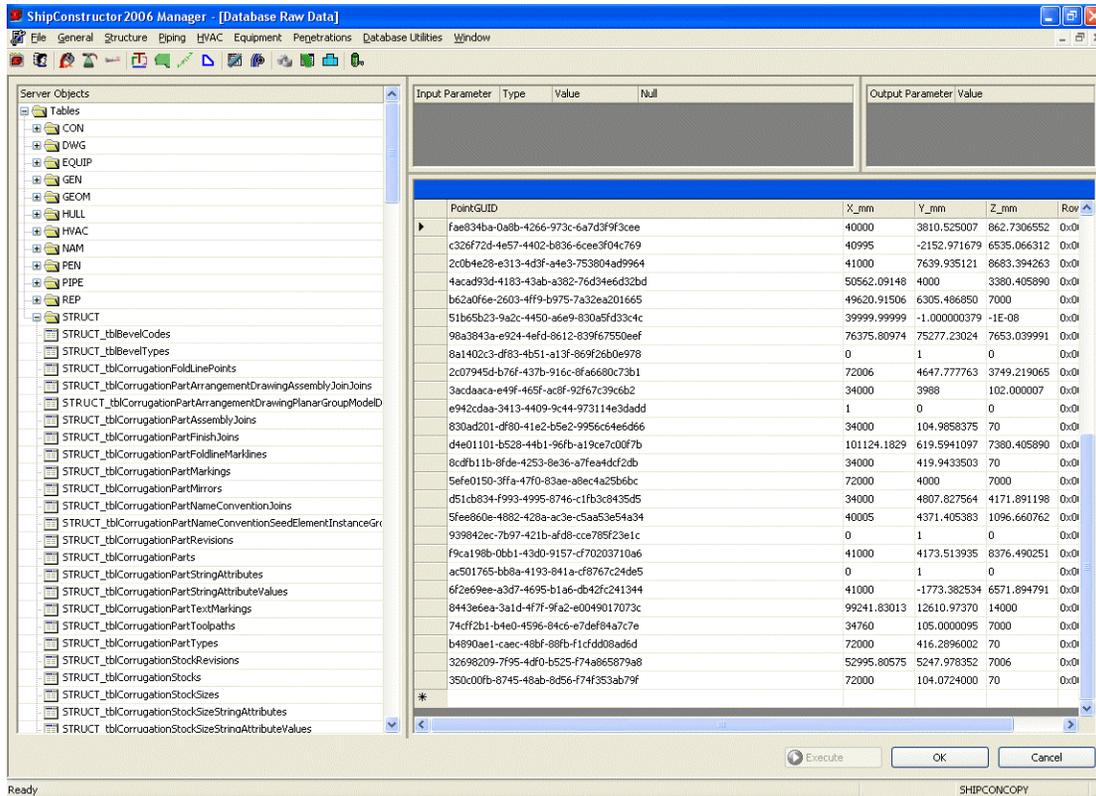
Figure 3.2 Screenshot of ShipConstructor Database Management

3.2   Importation of Ship Model Into Trident FEA

Since the prototype tool has to extract the data necessary for structural FEA, it was not sufficient to simply extract geometric data. As a minimum physical data such as plate materials and thicknesses is also needed, but semantic and contextual data such as object type and connection arrangements would also be helpful.

There were two architectural choices for importing data from ShipConstructor into the prototype tool:

1. standard geometry data translation formats such as IGES and/or STEP (AP203) could have been used to get the geometric data, and an XML data format could have been devised to pass the additional data, or

2. the ShipConstructor database API[1] could be used to directly access the ShipConstructor database from the prototype.

Option 2 was chosen for a number of reasons. Most importantly, it was felt that it would allow the most flexibility in terms of extracting data in the format that was required. For instance, it was acknowledged that structural geometry could be accessed at a number of different levels of fidelity, and the one most suitable for the given analysis could be chosen. Option 1 supported exporting only the most detailed representation of the data to IGES/STEP. Also, because the API provided access to virtually the full database, no additional (XML) interchange format would need to be devised and implemented in ShipConstructor to pass physical and semantic data.

There was one major drawback to choosing Option 2, however, in that there was no way to access non-planar structural plate data through the API. This is a result of the way ShipConstructor treats such non-planar surfaces in an "on-the-side" manner (i.e. through ShipCAM). Given the prototype nature of the work, this limitation was not felt to be critical.

3.3   The Prototype Tool

The devised prototype allowed for extraction and importation of ShipConstructor model data into a tool that supported preprocessing the data for export to the desired analysis package. It is felt that this intermediate tool is central in the long-term vision of using SPMs to supply data to multiple analysis packages, as the data requirements of each can vary significantly. The SPM system may support multiple representations of the data (as ShipConstructor does), which will go a long way to meeting the requirements of a variety of analysis packages, but it is felt that in most cases the SPM cannot supply data directly to a given analysis package without some degree of intermediate preprocessing. This preprocessing may include:

1. further simplification of the data beyond what the SPM can achieve natively
2. dimensional reduction of structural members if the SPM stores them in thin-walled solid form
3. modification to the geometry to represent a coherent moulded-form model (e.g. translating surfaces to midplane and extending surfaces to fill gaps)
4. healing minute modeling inconsistencies which may be fatal to the particular analysis
5. "equivalencing" a model by introducing intersections and imprints between surfaces which interfere geometrically.

The prototype tool provides functionality addressing items 2, 3 and 5 above. It supports the extraction of specific structural members from a ShipConstructor database (via its API), provides a capability to convert solid models to sheet models (if required; this step could be bypassed by extracting sheet models directly through the API), and translating and/or extending sheets to join up properly to form a midplane moulded-form model. Figures 3.3 and 3.4 contain screen shots from the prototype tool that show an example of some extracted data and a single plate isolated from this data. After extraction a model could then be

---

[1] An API (Application Program Interface) is a set of routines, protocols and software tools that act as a set of building blocks which are used by program developers to build software applications. Such applications share the common functionality provided by the API.

equivalenced and meshed before being sent to the Trident FEA tool for analysis. In Figure 3.5 a mesh of the sample isolated plate from Figure 3.4 is shown.
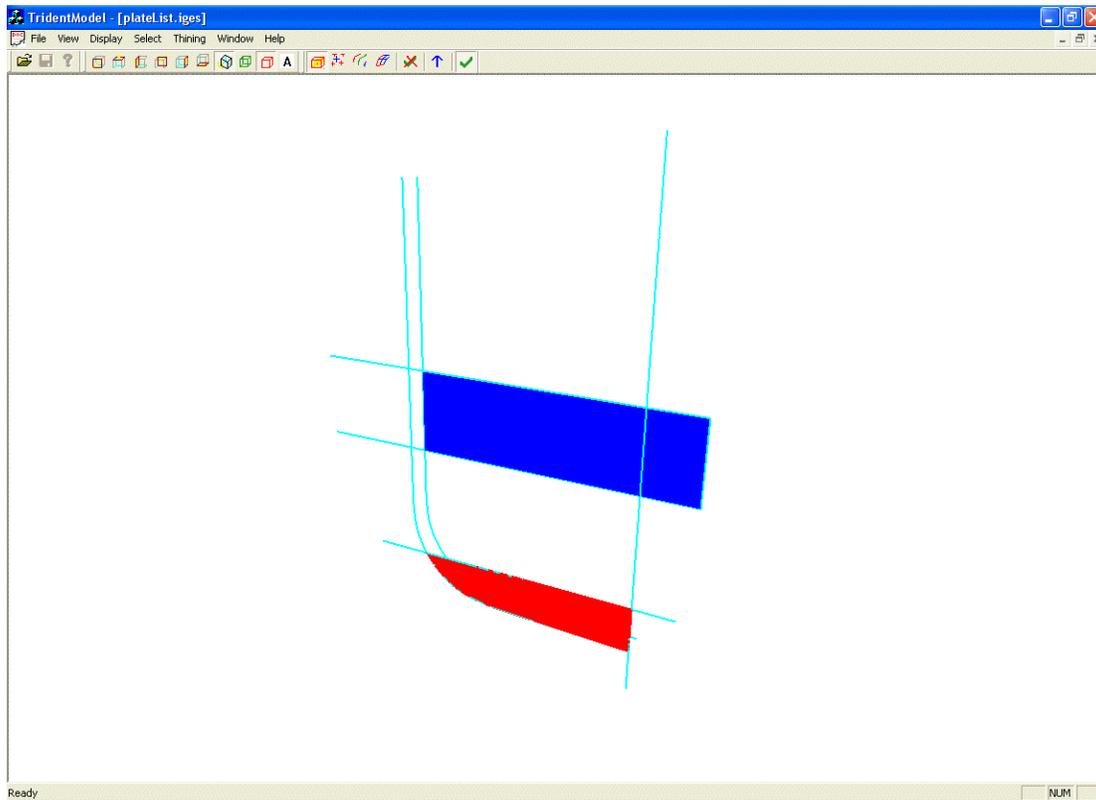

Figure 3.3 Sample of Extracted Geometric Data from a Ship Database
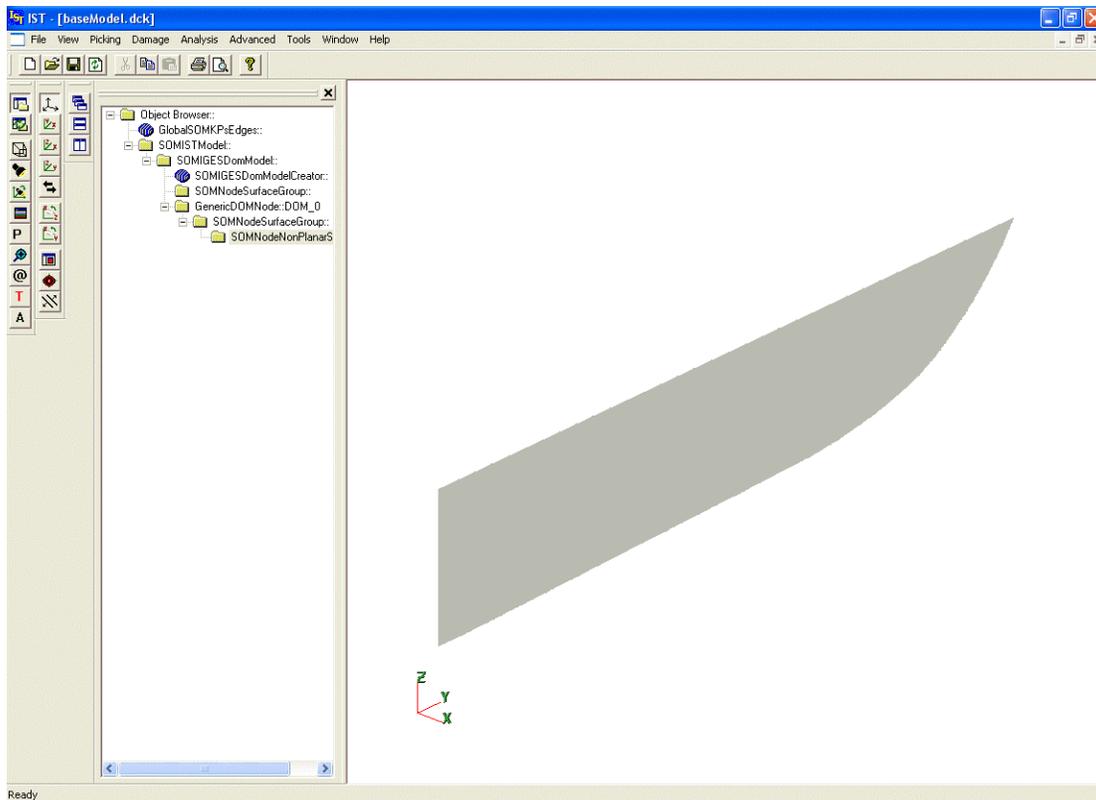
Figure 3.4 Isolated Plate from Sample Extracted Database Data
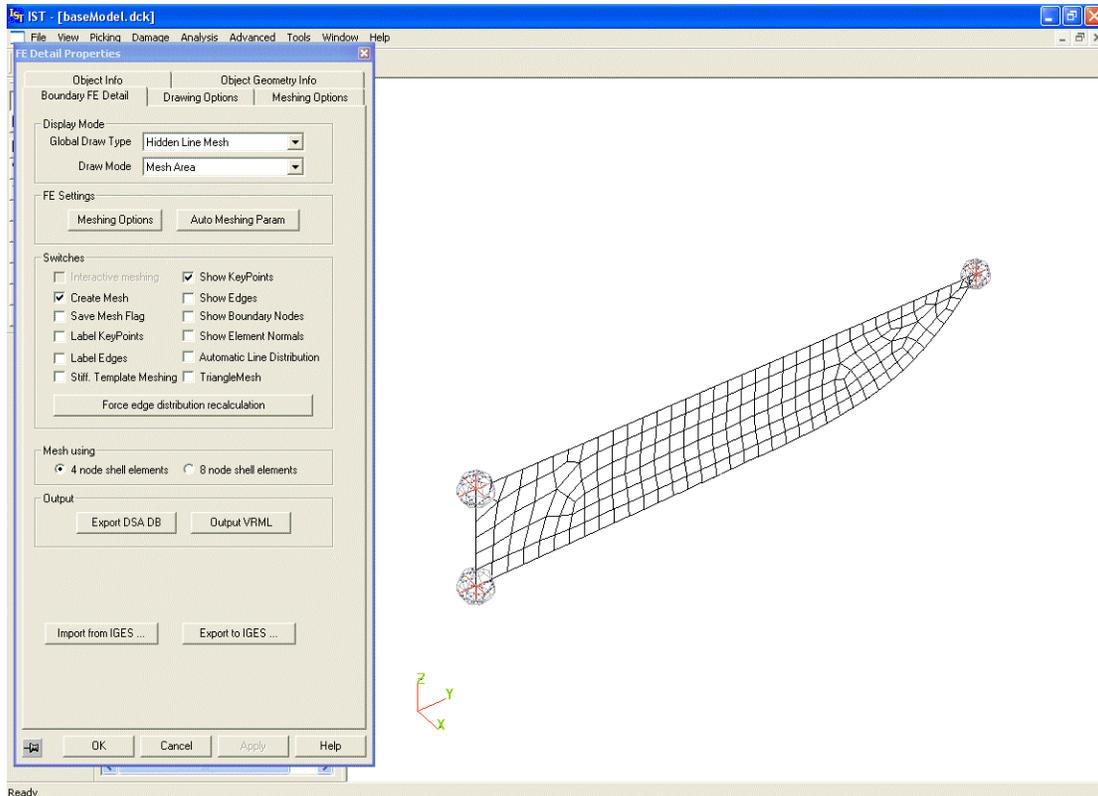
Figure 3.5 Finite Element Mesh on Sample Isolated Plate

3.4   Beyond the Prototype

The prototype illustrated the critical steps required in bridging the gap between SPM ship database systems and specialized analysis programs – namely the extraction of required data and the preprocessing of that data for the analysis tool. The prototype was somewhat limited in its scope, particularly with regard to automation of the preprocessing steps. The prototype required user intervention to drive the supported preprocessing steps, whereas it is felt that many of those steps can be automated in a final solution. Such automation will be necessary to support extracting models of significant size (the prototype used very small models suitable for detail FEA only). For instance, if a model of the CPF is to be imported for global FEA, it would be unreasonable to expect a user to manually work through items 2-5 described in the preceding section.

4. Review Of Available Commercial Ship Databases

A review has been done for the following CAD/CAM tools:
- CADDS5
- Tribon
- Foran
- CATIA
- Intergraph
- ShipConstructor

The information presented here is mainly from the product websites or user manuals. This review concentrates on the basic functional modules used in ship preliminary design and detail design phases, so in each CAD/CAM tool, functions/modules for preliminary design and detail design are listed.

4.1 CADDS5

CADDS 5i Hull is the module related to all phases of the ship design process. All preliminary design data including hull surface, coordinate reference, seam and butt lines, frame lines, etc. are saved in a single CADDS part consisting of different layers.

The detail design module is called "Advanced Structural Modeling". When doing the detail design, a user has to use the preliminary design part as a reference and create a detail structural member based on the data in the preliminary design model.

The single preliminary design model and the collection of detail design models can be used for FE analysis.

Comments: CADDS5i is owned by Parametric Technology Cooperation. The company wants to replace CADDS5i with Pro/E and has no plans to do any further development for CADDS5i. Any development for CADDS5i is totally financed by customers. According to the description in the company's website, there is no STEP interface.

4.2 Tribon

Tribon has been developed specifically for the ship industry (unlike other, general purpose CAD systems). Tribon provides tools that cover the entire ship design process.

Comments: Tribon, owned by AVEVA, is arguably the world's number one ship structural design software tool and has the largest user base in the ship industry. It has a complete suite of STEP protocols.

4.3   Foran

The module structure of Foran:

FORAN Subsystems
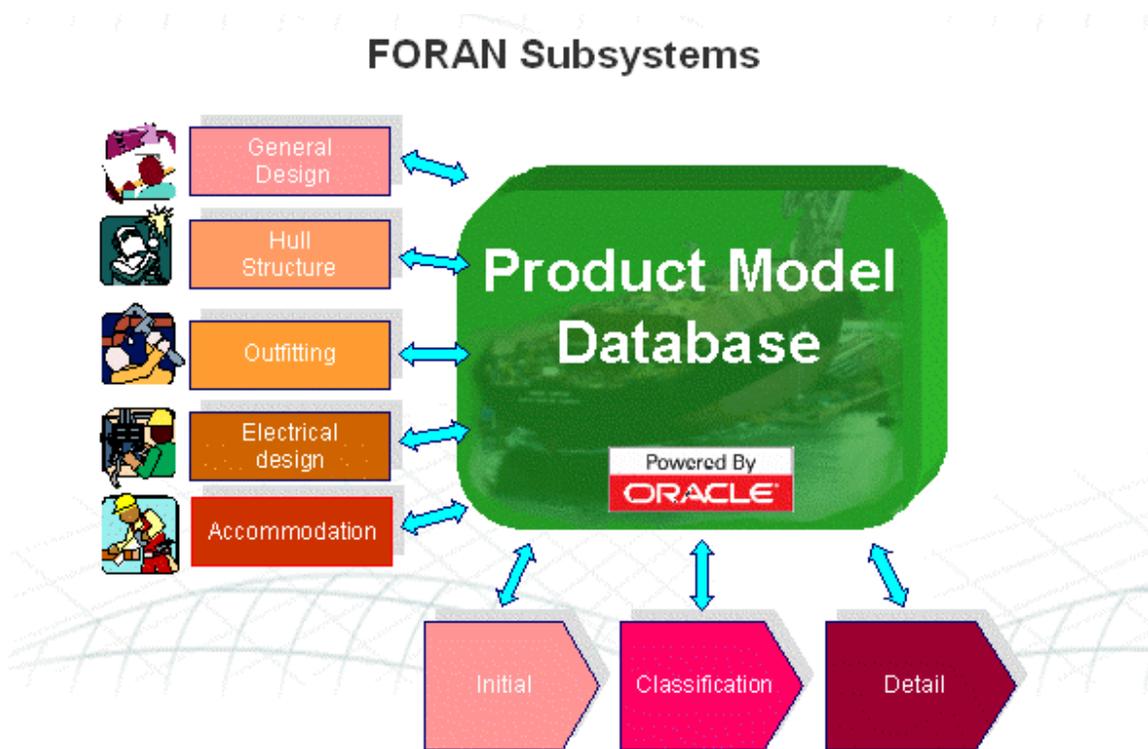
Figure 4.1 FORAN Suite

Like Tribon, Foran has been designed specifically for the ship industry.

Comments: Similar in functionality to Tribon, but it has much smaller user base.
.

4.4   CATIA

CATIA is a new entry to ship industry, and as a result, has a limited user base. The preliminary design module is "Structure Functional Design" and the detail design module is "CATIA Ship Structure Detail Design". The preliminary design module saves the preliminary design model in one or many CATIA parts, and the detail design will be driven by the parts generated in the preliminary design stage

Comments: The demo in Martec Limited from CATIA shows that the tools for ship design are still in beta form. The STEP protocol is not complete.

4.5 Intergraph.

Intergraph is mostly used by the US Navy as a ship design package. Intergraph's Vehicle Design System (I/VDS) is the package for ship preliminary design and the detail design package is Intergraph's Vehicle Structural Design System (I/STRUCT).

Comments: Except the US Navy, we don't know any customer which use Intergraph for commercial ship design.

4.6 ShipConstructor.

ShipConstructor, by ShipConstructor Software Inc. (SSI), is a fast-growing player in the ship CAD industry. Built around Autodesk's AutoCAD application, it allows for complete modeling of all aspects of a ship, including structure, piping, HVAC, etc. Historically (up to and including version 2005), ShipConstructor was primarily focused on modeling for purposes of ship construction and was not particularly strong in the preliminary design phase. Versions 2006 and beyond, however, have incorporated their Database Driven Relational Object Model (DDROM) technology which aims to provide a relational-CAD capability whereby objects, through their relationships to other objects, are automatically updated to reflect modeling changes. This technology makes ShipConstructor more attractive to the preliminary designers since common structural changes can be quickly made and the model automatically updated through the DDROM mechanism.

ShipConstructor 2006 stores all of its data in a SQLServer database (versions before 2006 mixed data storage between the database as well as AutoCAD drawing files). It provides export via standard CAD formats such as STEP, IGES and ACIS/sat. In addition, SSI has an API that allows access to the "raw" data in the SQLServer database. It is worth noting, however, that this API does not provide access to any "freeform" (e.g. shell, camber deck) structural constructs.

Comments: as stated above, it seems ShipConstructor is moving toward being more concerned with earlier phases of ship design, but has historically focused on the later phases. It is the opinion of the writer that the latest version of ShipConstructor can indeed be used for modeling a preliminary design model, but it is up to the modeler to do so – i.e. nothing to force a user to create a preliminary design was observed. Based on somewhat limited experience with the API, it seems well suited to extracting data in a variety of levels of detail not otherwise possible using standard CAD exchange formats.

5. Conclusions

All of the analytical tools require geometric data as well as property data. Geometric model requirements vary from one analytical tool to another. Global structural FEA and high frequency acoustic tools require relatively coarse geometric models whereas detailed structural FEA, infrared and radar tools typically require relatively detailed descriptions of the geometry. While the level of fidelity for geometric models can vary greatly, such geometric models are based on the same basic ship geometry, which all databases contain. On the other hand, the different analytical tools require different properties. Structural analysis tools require section properties as well as structural properties of the materials. Radar analysis tools will require a description of radar-absorbing coatings. At this time it is not clear what properties can be stored in and extracted from the various commercial databases.

Extraction and manipulation of data, be it geometric data or properties, can be done by way of:
- an industry-standard data exchange mechanism (i.e. STEP or IGES), or
- developer toolkits (API's) that allow low-level access to geometric data and/or other properties, or
- scripting tools.

It is important to note that different versions of STEP support different types of data. STEP AP 218 includes material properties. Because of such features, it is expected that STEP AP 218 would be the preferred industry-standard data exchange mechanism for data extraction. As pointed out in the preceding sections, a number of the commercial databases have some STEP support. ShipConstructor, CATIA and Intergraph provide a developer toolkit (API) thus permitting some degree of low-level data access. Other database packages, such as CADDS5 provide scripting tools. More investigation is required in order to develop a better understanding of the capabilities and potential of these scripting tools.

As a result of this investigation, the authors believe that a comprehensive developer toolkit (API), that permits the extraction and manipulation of geometric and property data, such as the one in ShipConstructor, is required. Such an API should allow access to parametric descriptions of the ship geometry that allow re-definition of geometry thereby making it possible to:
- filter out fine geometric data when such details are not required by the analytical tools and to
- extract an isolated portion of the ship as is typically required for a detailed structural FE analysis.

Since four of the categories of analytical tools involve structural analyses, structural properties will be very important. Hence the geometric data to be extracted from the ship database should also include structural properties, such as descriptions of beam sections and plate thicknesses. While it would be ideal for this data to be in the form of dimensions or structural properties (i.e. area, moments of inertia, etc.) it is possible that standard mill section names (WT155X43) might be stored instead.

In addition, structural material descriptions should also be available. Ideally, it would be possible to extract the actual structural properties (Young's Modulus, Yield Stress, etc). Such

descriptions might take the form of a material name (example, an HY80 steel) plus additional material requirements (heat treatment, etc.)

Creation of a more detailed description of the data requirements will require further investigations.

6.   References

1. ANSYS, (2006). "ANSYS Emag", http://www.ansys.com/products/emag.asp
2. Atlantis Scientific Inc., (1999). "DRMS Processing Software Reference Manual", Contractor Report, Nepean, ON. (DRDC Contract No. W7714-8-0153.
3. CSS (2006). "Computer Aided Design of Radar Cross Section", http://www.cadrcs.com
4. DRDC Atlantic, (2005), "Organic Radar Absorbing Materials", http://www.atlantic.drdc-rddc.gc.ca/articles/RAM_DLP_Article_e.shtml
5. Freeman, T (1996). "What is Imaging Radar", Jet Propulsion Laboratory, USA.
6. Huber, T.A. (2003), "A Literature Review of Polyaniline, Part 1. Polyaniline as a Radar Absorbing Material", DRDC Technical Memorandum, TM 2003-014.
7. Kashyap, S. (2006). Private Communication.
8. Lagali, N.S., "The Development of an Analysis Tool for the Reduction of Ship Radar Cross Section (U)", Research Note RN4/96, Canadian DND, Operations Research Division, maritime Forces Atlantic Headquarters.
9. NASA-GSFC, (2005). http://imagine.gsfc.nasa.gov/docs/science/know_l1/spectrum_chart.html
10. NAVAIR Systems Command (1999). "Electronic Warfare and Radar Systems Handbook", https://ewhdbks.mugu.navy.mil/rcs.htm
11. Remcom (2006), http://www.remcom.com/xgtd/
12. Roke Manor Research (2006). http://www.roke.co.uk/sensors/epsilon/cad_generation.asp
13. SAIC (2006). " Xpatch Overview", http://www.saic.com/products/software/xpatch/
14. Surface Optics Corporation (2006): "Radbase. Radar Cross Section Simulation and Analysis", http://www.surfaceoptics.com/Products/ModSim/RadBase.htm
15. Tripoint Industries, Inc. (2006). "Lucernhammer", http://lucernhammer.tripointindustries.com
16. Wikipedia (2006), "Radar Cross Section" , www.wikipedia.org/wiki/Radar_Cross_Section.
17. Trueman, W. and Paknys, R. "RPO Version 1Q", Corcordia University EMC Lab, Dept. of Electrical and Computer Engineering, Contract W7707-010074/001/HAL, Progress Report, Prepared for DCRD Atlantic, December 2005.
18. Davis Engineering (2004a), http://www.davis-eng.on.ca/dresball.htm
19. Davis Engineering (2004a), http://www.davis-eng.on.ca/eductdiff.htm
20. Davis, W.R. and Thompson, J. (2002). "Developing an IR Signature Specification for Military Platforms Using Modern Simulation Techniques", Presented at the SMi Conference: Pursuit of Stealth, London, March 11, 2002.
21. Reid, F. and Rouleau, E. (2004). "Description of an Infrared Signature Analysis Software, WinISAS. Technical Manual and Tutorial", DRDC Valcartier TR 2002-117, DRDC Valcartier.
22. ThermoAnalytics (2001). http://www.thermoanalytics.com/products/muses/index.html
23. Vaitekunas, D.A, Fraedrich, D.S. (1999). "Validation of the NATO-Standard Ship Signature Model (SHIPIR), SPIE 3699.
24. Vaitekunas, D.A, Lawrence, O.E., (1999). "Infrared Scene Capabilities of SHPIR", SPIE Targets and Backgrounds: Characterization and Representation V, a group of

sessions held at the AeroSense Conference of SPIE, April 5-7, 1999, Orlando, Florida. pp.92-102.

25. Vaitekunas, D.A., Alexan, K., Lawrence, O.E., and Reid, F. (1996). "SHIPIR/NTCS: a naval ship infrared signature countermeasure and threat engagement simulator," SPIE 2744, pp. 411-424, 1996.

26. Wikipedia (2006a). http://en.wikipedia.org/wiki/Infrared#Different_regions_in_the_infrared

27. Wikipedia (2006b). http://en.wikipedia.org/wiki/Infrared

28. Hally, D. (2006). Private Communication, 2006.

29. Hally, D. (2002). "TRANSOM Calculations of Flow Past SSPA 720", (DREA TR 2001-167), DRDC Atlantic.

30. Hally, D. and Watt, G.D. (2001). "RANS Calculations of the Evolution of Vortices", (DREA TR 2001-216), DRDC Atlantic.

31. Hally, D., "A Multi-Method Solver for Flow Around Ships", DREA-SL-1999-049, DRDC Atlantic.

32. Hally, D. (1997). "TRANSOM: A Multi-Method Reynolds-Averaged Navier-Stokes Solver: Overall Design", (DREA TM 97-231). DRDC Atlantic.

33. Hally, D. (1997). "Implementation of a Finite Element Navier-Stokes Solver in TRANSOM", (DREA TM 97-225). DRDC Atlantic.

34. Smith, M.J., "SNAP – The Ship Noise Analysis Program Version 1, User's Manual", Martec Limited, 1998.

35. Slater, J. and Norwood, M, "Naval Ship Structural Analysis for Underwater Explosions", Proceedings of the Second Canadian Marine Dynamics Conference, pp. 176-184, Vancouver, B.C., August 9-11, 1993.

36. Cole, R., Underwater Explosion, Princeton University Press, 1948.

37. Hicks, A.N, "Theory of Explosion Induced Ship Whipping Motions", Naval Construction Research Establishment, Report No. NCRE/R579, March 1972.

38. DeRuntz, J.A., Geers, T.L., and Felippa, C.A., "The Underwater Shock Analysis Code (USA-Version 3)", Defense Nuclear Agency, Washington, DC, Report 5615F, 1980.

39. Combustion Dynamics Limited – CHINOOK 2005 User's Manual, Software Manual # SM-04-12, Martec Ltd., 2005.

40. Norwood, M., Kumar, R. and Palmeter, M., "Computer Codes for Response Analysis of Naval Structures to Underwater Explosions", User's Manual, Martec Ltd., April 1990.

41. Norwood, M., Kumar, R. and Palmeter, M., "Computer Codes for Response Analysis of Naval Structures to Underwater Explosions – Phase II", Final Report, Martec Ltd., April 1990.

42. Norwood, M., "Summary Report on DRES UNDEX Contracts", Final Report, Martec Ltd., July 2002.

43. Trident UNDEX Application Interface: User's Manual, Martec Ltd., December 2005.

44. Trident FEA 2004: User's Manual, Martec Ltd., SM-04-06, Original: August 2004, Updated: August 2005.

45. Vibration and Strength Analysis Program (VAST), Version 8.6: User's Manual, Martec Ltd., August 2005.

46. Best, J.P., "The Formation of Toroidal Bubbles upon the Collapse of Transient Cavities", J. Fluid Mech., Vol. 251, pp. 79-1087, 1993.

47. Amdahl, J., Hu, C., Prince-Wright, R., Reissman, R.C., Shyu, R.J. and Yoshida, K. (1997). "Structural Design against Fire and Blast", 13th International Ship and Offshore Structures Congress, Trondheim, Norway, Vol. 2, pp. 43-77

48. API (1996). "Supplement 1 to Recommended Practice for Planning, Designing, and Constructing Offshore Platforms – Working Stress Design, American Petroleum Institute (API) Recommended Practice 2A-WSD, 20th Edition.

49. Baker, W.E., Cox, P.A., Kulsez, P.S., and Strhlov, R.A. (1983). Explosion hazards and Evaluation, Elsevier Scientific Publishing Co., Amsterdam.

50. Biggs, J.M., Introduction to Structural Dynamics, McGrawHill Inc. New York, New York, 1964

51. Combustion Dynamics Group (CDG), Chinook 2005 Manual, Software Manual #SM-04-12, Martec Ltd., Halifax, NS, 2005

52. Houlston, R., Slater, J.E. and Ritzel, D.V. (1991). "Damage Assessment of Naval Steel Panels Subjected to Free-Field and Enhanced Blast Loading", Advances in Marine Structures – 2, Smith, C.S. and Dow, R.S. Ed., pp. 416-433.

53. "Interim Guidance Notes for the Design and Protection of Topside Structures Against Explosion and Fire" (1992), The Steel Construction Institute Document No.: SCI-P-112/454.

54. Jones, N. (1971). "A Theoretical Study on the Dynamic Plastic behavior of Beams and Plates with Finite Deflection". Solids and Structures, Vol. 7, pp. 1007-1029.

55. Kingery, C.N. "Air Blast Parameters Versus Distance for Hemispherical TNT Surface Bursts", BRL Report 1393, Aberdeen Proving Ground, Maryland, 1968.

56. Koko, T.S. (1990). "Super Finite Elements for Nonlinear Static and Dynamic Analysis of Stiffened Plate Structures". PhD, Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada.

57. Koko, T.S. and Olson, M.D. (1991). "Nonlinear transient response of stiffened plates to airblast loading by a super-element approach". Computer Methods in Applied Mechanics and Engineering, Vol. 90, pp. 737-760

58. Koko, T.S., Brennan, D.P., Norwood, M.E, MacAdam, T., and Rushton, P.A., "MASTSAS (MAST Structural Analysis Software) Version 1.1, Reference Manual", Martec Technical Report No.: TR-02-26, August 2002.

59. Koko, T.S., Gallant, B.K. and Tobin, S.M. "Investigation of Plastic Zone Development in Dynamic Tear Test Specimens", Contractor Report, DREA CR 1999-095, July 1999.

60. Lloyd's Register (2000). "Rules and Regulations for the Classification of Naval Ships", Vol. 1, Part 4: Military Design.

61. Melton, W., Beach, J, Gagorik, J., Roseman, D. and Sikora, J. (1994). "Advanced Double Hull Research and Development for Naval and Commercial Ship Application", SNAME Transactions, Vol. 102, pp. 295-323.

62. Naval Civil Engineering Laboratory (NCEL), FRANG User's Manual, Version 1.0, NCEL, January 1988.

63. Naval Civil Engineering Laboratory (NCEL), SHOCK User's Manual, Version 1.0, NCEL, January 1988.

64. Norwood, M.E. (1994). "Computer Codes for Response Analysis of Naval Structures to Underwater Explosion: Phase II Final Report", Prepared for DRES.

65. Polcyn, M.A., Ketchum, D.E., Koko, T.S., and Rushton, P.A. (2005), "Supplemental Design Guide for Blast, Final Report for Contract No. DTCG39-99-E00220", submitted to SSC, May 2005.

66. Schuback, R.B., Olson, M.D. and Anderson, D.L. (1993). "Rigid-Plastic Modeling of Blast-Loaded Stiffened Plates – Part I: One-way Stiffened Plates, Part II: Partial End

Fixity, Rate Effects and Two-way Stiffened Plates". Mechanical Sciences, Vol. 35, No. 3-4, pp. 289-306

67. Structural Practices Standard for Canadian Forces Steel Surface Ships (1993), D-03-002-008/SG-003, DND.

68. TM5-1300 (1990). "Structures to Resist the Effects of Accidental Explosions" Army TM5-1300, Navy NAVFAC P-397, Air force AFR88-22.

69. Trident FEA 2004 User's Manual, Martec Limited, SM-04-06, August 2004.

70. Lin, F. "FD-WaveLoad 2006A User's Guide", Martec Technical Report SM-06-02 a rev 3, Halifax, Nova Scotia, 2006.

71. van't Veer, A.P., Willemstein, A.P., Huijismans, R.H.M., "Precal V6.0 User's Manual", Maritime Research Institute Netherlands, Wageningen, The Netherlands, July 2003.

72. McTaggart, K.A., "SHIPMO7: An Updated Strip Theory Program for Predicting Ship Motions and Sea Loads in Waves", DREA, Technical Memorandum 96/243, March 1997.

73. Petten, D., "Comparison of the CPF Vertical Bending Moment Determined by Different Methods", Martec Technical Report TR-06-08, Halifax, Nova Scotia, February 2006.

74. D. Brennan and R. Dow, "Development of a Trident-SPM Interface", (2005), Martec Technical Report TN-05-43.

This page intentionally left blank.

DOCUMENT CONTROL DATA				
(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)				

1.	ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) MARTEC Limited, 1888 Brunswick Street, Suite 400, Halifax, Nova Scotia, Canada, B3J 3J8		2.	SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable). UNCLASSIFIED
3.	TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title). Single High Fidelity Geometric Data Sets for LCM – Model Requirements			
4.	AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.) Brennan D., Koko T., Mackay K., Norwood M., Tobin S., Teng E., Wallace J.			

5.	DATE OF PUBLICATION (month and year of publication of document) November 2006	6a. NO. OF PAGES (total containing information Include Annexes, Appendices, etc). 89	6b. NO. OF REFS (total cited in document) 69

7.	DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered). CONTRACT REPORT
8.	SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include address). Defence R&D Canada - Atlantic PO Box 1012 Dartmouth, NS, Canada B2Y 3Z7

9a.	PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant). 11 gk 14	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written). W7707-053123/001/HAL
10a	ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.) Martec Technical Report TR-06-18	10b OTHER DOCUMENT NOs. (Any other numbers which may be assigned this document either by the originator or by the sponsor.) DRDC Atlantic CR 2006-134

11.	DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification) (X) Unlimited distribution ( ) Defence departments and defence contractors; further distribution only as approved ( ) Defence departments and Canadian defence contractors; further distribution only as approved ( ) Government departments and agencies; further distribution only as approved ( ) Defence departments; further distribution only as approved ( ) Other (please specify):
12.	DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected). UNLIMITED

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

Over the past decade, the ship building industry has begun to develop and use Single Product Models (SPMs) for improving the management and efficiency of design, analysis and construction of commercial and naval vessels. SPMs are extensive single 3D CAD data models incorporating hull structure, propulsion, steering, piping, electrical, HVAC and other systems, which make up a complete ship. Ship classification societies and navies (most notably the USN in their DDX project) have ongoing R&D efforts to bring this technology to its full potential. This work involves leading software providers, including Tribon, Catia and ShipConstructor who are developing products, training and documentation to facilitate the use of SPMs by ship builders and design authorities. It is reasonable to expect that future DND vessels will be designed and built using SPMs. During this same period of time, DND has had an ongoing R&D effort in developing computer-aided ship data and analysis programs to improve the efficiency of Life Cycle Management (LCM - maintenance) of its fleet. Martec Ltd has been extensively involved in this work, most notably through the DRDC ISSMM (Improved Ship Structures Maintenance Management) TDP which successfully demonstrated the concept of using a CAD-like database of the HALIFAX class along with advanced sea load and structural analysis methods to determine the effects of structural damage on a vessel's ability to undertake intended operations. The ISSMM project, as well as other DND programs such as the Structural Inspection Database (SID) and the TRIDENT program, which is a general purpose ship structural analysis tool recently developed further by Martec to address FELEX issues, provide an extensive set of software tools to address structural LCM issues. There is strong interest by ship owners and agencies (including DND and ship Classification societies) and the SPM software producers to extend the SPM applications beyond design and construction to the LCM of ships. Doing so would eliminate the time consuming and costly production of separate analysis models required as input to a number of DND's suite of lifecycle maintenance analysis tools.   This offers significant potential savings in operation and maintenance costs as well as improved understanding and confidence in vessel safety. The work proposed under this contract will provide the first steps towards developing a link that can bridge the gap between these LCM analysis tools and data stored in a SPM database. For its part, Martec Limited has worked extensively with DRDC-Atlantic in both the development and application of many of these LCM analysis tools, and has recently initiated an in-house R&D program focused on developing SPM/LCM data exchange links. This corporate experience has enabled Martec to offer a uniquely qualified and strong team that can meet the requirements of the proposed R&D effort.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

Single Product Model
Life Cycle Management
structural finite element analysis
ship hydrodynamics
radar signature
infrared signature
electric potential signature
cathodic protection
magnetic signature
acoustic signature
flow noise
CADDS5
Tribon
Foran
CATIA
Intergraph
ShipConstructor.

This page intentionally left blank.

This page intentionally left blank.

Defence R&D Canada

Canada's leader in defence
and National Security
Science and Technology

R & D pour la défense Canada

Chef de file au Canada en matière
de science et de technologie pour
la défense et la sécurité nationale

DEFENCE **R&D** DÉFENSE

www.drdc-rddc.gc.ca